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THE

BRITANNIA AND CONWAY

TUBULAR BRIDGES.

VOL. II.

THE

BRITANNIA AND CONWAY TUBULAR BRIDGES.

WITH

GENERAL INQUIRIES ON BEAMS
AND ON THE
PROPERTIES OF MATERIALS USED IN CONSTRUCTION.

BY

EDWIN CLARK,
RESIDENT ENGINEER.

PUBLISHED WITH THE SANCTION, AND UNDER THE SUPERVISION, OF
ROBERT STEPHENSON.

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SECTION V.

HISTORY OF THE DESIGN.

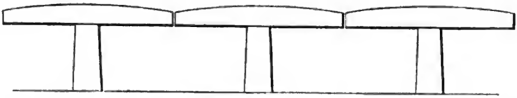
CHAPTER I.

ORIGINAL INTENTIONS WITH RESPECT TO THE ERECTION OF THE BRIDGES.

January to July, 1846.

In continuing the History of the Design, that has been brought down to the beginning of 1846 by Mr. Robert Stephenson, it will be necessary to enter more in detail into the then state of the investigations connected with the bridges. The first drawings for the tube, made in the month of March, were not prepared with any intention of determining definitely the details of the intended structures. The experiments were commenced in July 1845, and had been continued, with little intermission, by Mr. Hodgkinson and Mr. Fairbairn, down to this period; and the joint report of Mr. Stephenson and these gentlemen was prepared in February 1846. These experiments and drawings formed the principal foundation for future progress. In the months of

March and April 1846, Mr. Stephenson devoted considerable time and patience to explaining to the Author his then views and intentions on the subject of the bridges. These views were carefully recorded, and will be extracted, frequently *verbatim*, from a note-book of office minutes, kept by the Author, in which every deliberation, and every instruction, has been minutely recorded. The drawings and sketches then in existence were designs for rectangular and oval tubes, of sufficient dimensions for a span of 450 feet. The experiments had fully corroborated the opinion expressed by Mr. Stephenson in his evidence as to the feasibility of making such structures of sufficient strength to support themselves without any extraneous assistance; it had been also ascertained that to resist the flexure or buckling of the top, it would be necessary that this portion of the structure should be considerably thicker than the bottom, though the exact proportion was undetermined. The rectangular form, and the use of cells, or corrugations, had likewise been definitely settled; and in order to arrive at the approximate weight of such a structure, the thickness assumed to be necessary varied in different parts from half an inch to an inch; these dimensions having reference solely to the Britannia Bridge. Mr. Stephenson relied considerably on the important addition to the strength of this bridge from its being a continuous beam; in some of the drawings the beam was represented as separated at the middle of each span, and thus balancing on the piers. The depth of this tube was taken at about 30 feet, as being one-fifteenth of the length, the usual proportion adopted in cast-iron flanged girders, of which he considered



this a modification; this would, moreover, afford sufficient height for the passage of a locomotive; and as he proposed constructing a double line of such tubes, the width was settled at 15 feet, as being sufficient for a single line of railway, with room for persons inside the tube to be out of danger during the passage of trains. It was intended that the two lines of tubes should be entirely independent of each other as regarded vertical support, though it was thought that it would be necessary to brace them together horizontally to resist the lateral pressure from the storms so prevalent in their intended locality. The dimensions of the masonry for the piers were not yet settled, nor were any details of the construction of the tubes agreed upon; it was predicted that the union of the plates by means of rivets would be so complete, that the structure might be considered as one homogeneous mass; the properties of such a mass were then considered in detail; the changes of form to which it was considered liable were as follows:—First, from alterations of temperature; secondly, from the effect of winds; and thirdly, from a passing load.

First,—Alterations of temperature. The extreme range of temperature to which it would be subjected was taken at 75° Fahrenheit, within which limits malleable iron alters in length about one two-thousandth part of its original dimensions;* each tube would thus vary in length, it was considered, about 2·7 inches, and the whole length of span about 8 inches. Now it was intended to construct a tower on the Britannia Rock in the middle of the Straits; and on either side of this central tower — at a distance of 450 feet — the two side-towers, their foundations being dry at low-water; and lastly, at either extremity of the bridge, at a distance of 230 feet beyond these towers, it was proposed to construct the abutments. The continuation of the tubes so far over the land was not adopted as the most economical means of crossing this space, but in order to obtain a counterpoise to the large tubes, so that the bridge should be one continuous beam from abutment to abutment, the whole length being 1512 feet. This continuous tube was to be secured in the Britannia tower, but was to be free to expand in both directions, either by passing over rollers in the side-towers and abutments, or by being there suspended on strong vertical links, which should be free to oscillate. The motion from expansion through each side-tower being taken at 2·7 inches, the motion in the abutments would be about 4 inches. It was also foreseen that a slight curvature would take place in full sunshine, the tube becoming convex towards the sun.

---

* Wrought-iron expands or contracts one ten-thousandth of its length from a change of temperature of 15° Fahrenheit, or the same amount as from a direct longitudinal strain of 1 ton per square inch of section.

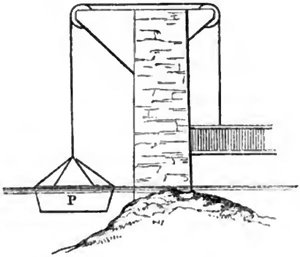
Secondly, with respect to the effect of wind, the pressure of a hurricane in this country was taken at 46 lbs. per square foot, which, exerted horizontally, would amount to a pressure of 277 tons on each tube, or 831 tons over the whole span, which, though considered as being much overrated, was yet not in any way likely to prove injurious to the combined tubes, more especially on account of the value of the inertia of so weighty a mass in resisting impact.

Thirdly, the passing traffic within one tube was estimated at an engine and tender and twenty carriages, or about 200 tons weight, which would be equivalent to 100 tons at the centre of the tube; but if filled with locomotives, the weight would be about one ton per foot run, or 450 tons in each tube; the deflection of the tubes from their own weight was estimated at one foot; and it is remarked, "this deflection will be but slightly increased by this load." The exact subsequent confirmation of these original views is certainly most extraordinary; the imaginary tube to which the minutes refer was then without definite form, and this was merely a conception of the probable properties of such a structure, should it ever exist as a reality: they referred to an ideal abstract beam, whose properties were determined from its resemblance to a cast-iron flanged girder; the thickness, the weight, and the method of construction, were all approximations, as the small experiments that had been made gave no data for any such results; and yet Mr. Stephenson was within less than an inch of the truth in assuming that the deflection of these tubes would be about one foot if constructed in accordance with the principles he suggested. To those who know the difficulties which beset the theory of the deflection of such a structure, this will appear the more remarkable. The amount was arrived at entirely by analogy; and Mr. Stephenson stood at the time almost alone in the conviction that no anomalies would occur from the union of plates by upwards of 300,000 rivets. The phenomenon of the curvature from the effect of local increase of temperature is similarly foreseen, and, in fact, the minutes generally require no modification to be applicable in detail to the present finished structure.

The other important subject now engrossing attention was the best method of erecting these tubes. Numberless suggestions had been made and discussed; we have seen that Mr. Stephenson had proposed constructing a cast-iron arch at Conway on a series of pontoons, and thus floating it to its place,—a process which he had discussed with Mr. Ross, his resident engineer at Conway.

Other propositions, though exceedingly ingenious, were quite impracticable; it was suggested by some friends to take advantage of the rise and fall of the tide—which varies from 14 to 21 feet—in the following manner:—

P is a pontoon, or tank, capable of holding sufficient weight of water to raise one end of the tube. The chain would pass from the pontoon over the tower, and be secured to the tube.



On the tide rising, valves would be opened in the bottom of the pontoon, on which it would fill with water; the valves would be then closed, and, as the tide fell, the pontoon would act as a counterpoise to pull up the tube through a space of about 17 feet.

The tube would then be secured in its raised position and the operation be repeated until the whole height of 100 feet were reached.

It is evident that the construction of brackets of sufficient length and strength to allow the pontoon P (which would be of great size) to come vertically beneath the drum, would be a matter of great difficulty; and the details of the plan generally would be impracticable.

Another method entertained for some time, instead of moving the tube bodily into its place, was to proceed in a similar manner as described for the construction of the cast-iron arch first designed for the bridge across the Straits,—viz., to commence the construction of the tube simultaneously at the centre tower and on each land tower, proceeding regularly and equally on each side of each tower, so as to ensure the balancing or equilibrium of each portion on its particular base, until the tubes thus prolonged met at the centre of each span, where they would be united, and the beam thus completed. One objection to such a mode of procedure is this, that at the point of union, at the centre of each span, there could have been no strain, the tubes thus depending solely for their strength on the very severe strain occurring in each tower; the bridge could only, indeed, have been considered as a continuous tube with respect to any additional weight that might come upon it, and not as regards its own weight, which is the most important element of strain. Another serious objection was the danger to be apprehended from gales of wind during the great length of time to which such an extensive surface, at so great a height, must have been exposed, the suspension-bridge, which would have been necessary in this method of construction, not being well suited to resist horizontal violence. This, and other similar suggestions, were therefore abandoned, and Mr. Stephenson had determined on erecting the bridge *in situ* in the following manner:—

He proposed, 1st. To construct a suspension-bridge of sufficient strength to carry the tube and any load that might be required: the platform, or roadway, of this bridge being at the intended level of the tubes.

2dly. To prepare platforms at the same level at each approach of the suspension-bridge, and on these platforms, as well as across the suspension-bridge, to lay down a railway.

3dly. To construct the tube on the railway on a line of trucks moveable bodily on wheels or rollers.

4thly. To load the suspension-bridge with a distributed weight, about equal to the intended tube, supported on a line of trucks on the suspension-bridge.

And lastly. To draw the tube thus supported on to the bridge at one end simultaneously with the withdrawal at the other end of the line of loaded trucks, so as to prevent any great undulation in the suspension-bridge.

The details of this suspension-bridge were consequently proceeded with by the Author in Mr. Stephenson's office: the weight which it would have to support was taken at 1100 tons, and it was thought prudent, with so unusual a weight, to increase the ordinary proportion of the versed sine to the span, in order to limit the tension of the chain, although at a corresponding sacrifice of stability. With a versed sine of 40 feet, the length of chain for the span of 450 feet would be 459·3 feet. The sectional area necessary for the chains was taken at 384 square inches, the maximum tension per square inch of section on these assumptions being 4·2 tons, or about the same amount as that proposed for the tension in the bottom of the tube itself independent of the chains.

To enable the reader to compare this suspension-bridge with other similar structures, we here subjoin some details of well-known suspension-bridges :—

	Span. Feet.	Sectional Area of chain. Square Inches.	Versine. Feet.	
Menai Bridge	580	260	43	Telford, 1820.
Conway Bridge	327	130	22·3	Ditto.
Hungerford Bridge	674	294	54·5	Brunel.
Clifton Bridge	703	480	70	Brunel.
Hammersmith Bridge	422·25	180	29·85	Tierney Clark.
Pesth Bridge	665	520	48·0	Tierney Clark.

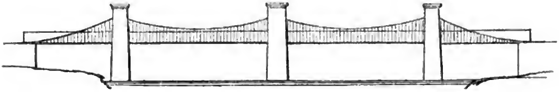
In designing this suspension-bridge a question naturally arose "as to whether the suspension-chains might not be made available as an additional support to the tube;" for the cost of removal, it was considered, would probably be even more than equal to the value of the chains themselves.

The question was, "not whether an amount of iron equal to the weight of the chains might not be applied in some better manner in strengthening the tube itself, but rather, what was the most feasible method of rendering the chains available as additional means of security, supposing them necessarily erected for the purpose of temporary scaffolding."

There occurred many very considerable difficulties in thus employing the chains; for it was calculated that "in each separate span, the lengthening of the chain from increase of temperature would amount at a maximum to 4 inches; and this lengthening of the chain, supposing it to hang freely, would increase the versed sine, or lower the central point about 9½ inches; but the rigid tube in the meantime merely expanding longitudinally, would at some times be wholly raised up by the chain, and at others totally unsupported."

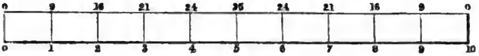
These difficulties had been foreseen immediately after the chains were proposed; and to obviate them Mr. Fairbairn had suggested that they should only be attached at the centre of each tube, in order to maintain a constant tension at all temperatures, and instead of securing the chains in the abutments at each end, as usual in suspension-bridges, he proposed that they should pass over rollers or pulleys in each abutment, a heavy counterpoise being suspended on the chain, which would rise or fall as they became longer or shorter from changes of temperature; the weight necessary for this counterpoise being estimated by him at about 300 tons. Such a weight would, however, be quite inadequate; the mere chain itself requiring a counterpoise of nearly 400 tons.

The method decided on by Mr. Stephenson was, first, to employ the chain to support a scaffold for the erection of the bridge, and ultimately to attach its extremities to a prolongation of the tube itself through each abutment, being careful to construct the bottom of the tube strong enough as a pillar to resist the horizontal pull of the chains. Expansion and contraction would then no longer lower the centre part of the chain, on account of a corresponding variation in the length of the tube itself, as in the figure below.



The saddle at the central tower, over which the chain would pass, would thus be unmoved, while the saddles in the side-towers would move through the same space as the corresponding portions of the tube. To effect this construction, it would be necessary, first, to attach the chains to the abutments at each end during the manufacture of the tubes, and, subsequently, to detach them, and secure them permanently to the tube.

The discussions respecting this method of applying a suspension-bridge led to numerous suggestions. It will be easily imagined how difficult it was to insure the joint action of a rigid beam with an unstable chain, how important it was to regulate definitely the amount of strain to be intrusted to each, and to devise practical means of insuring these objects. It was intended that the chains should support the tube ultimately by means of a flange riveted to the sides of the tube, for which purpose the rectangular form was particularly suitable; and if the support from the chain was to be principally limited to the centre of the tubes, it was considered advisable to reduce, if possible, those portions of the chain near the points of suspension into straight rods, to increase its stability. To determine the amount of strain, the following proposition emanated from a practical and theoretical philosopher. The strain in any beam from its own weight is proportionate to the rectangle of the segments at any point of its length; so that if the tube were divided into ten equal portions, as in the sketch below, the strain at each of these divisions would be represented by the figures; but if it were required that 16, for instance, should represent



the maximum strain which it was deemed prudent to permit, in that case it would not be necessary to apply any force at the first and second divisions, and at the rest such forces as would produce strains represented by

5 8 9 8 5.

The forces necessary would therefore be represented by

$$0 \quad 0 \quad 0 \quad \tfrac{5}{21} \quad \tfrac{8}{24} \quad \tfrac{9}{25} \quad \tfrac{8}{24} \quad \tfrac{5}{21} \quad 0 \quad 0 \quad 0.$$

If, therefore, a model chain were constructed, with weights hung from it proportional to these numbers, we should have the chain in a curve dropping at the middle much more than the common catenary.

With respect to the tubes themselves, it was always intended from their first proposal to construct them of sufficient strength in themselves, without in any way depending on chains for their support. It is difficult to retrace chronologically the numberless modifications which the general outline of this curious structure had undergone; but whether an elliptical or rectangular section, or a combination of the two, was the subject of discussion, the tube was always treated as a beam, of which the wrought-iron top and bottom were analogous to the top and bottom flanges of a cast-iron T-girder. The calculations of its strength were made on this assumption; and it was intended that the tension in the bottom should not exceed 5 tons per square inch of section from the weight of the tube itself; which, being about the same tension as that in the chains of the Menai Bridge, was considered practically sufficient, especially as in these calculations no account was taken of the strength of the sides in resisting transverse strain, on account of the want of any experimental knowledge as to the peculiar province of this portion of the structure. The bottom being in a state of tension, no apprehension was felt as to its preserving its form to whatever extent its dimensions might be carried; while the apprehensions with respect to the top related to the difficulty of retaining so long and peculiar a pillar in shape. We find, accordingly, that while the bottom has undergone but little modification since its first proposal, the top continued to engage special attention; and the detail of the sides was completely deferred until a later period, when experiment should furnish some guide for their construction.

The general features of the first drawings bear, however, a remarkable resemblance to the ultimate design; the rectangular form and the dimensions of the bottom were nearly the same, although there were no cells, for the practical question as to the best method of uniting together the intended area of plates had not been considered. The pillars of T-iron were not then introduced. The advantage of cells or corrugations for the top had become evident with the very first experiments, but the requisite thickness of the plates was much underrated; and on this account, as well as from the omission of the heavy covers and T-irons since used in connecting the plates, the total weight of the tubes was estimated much too low. As the experiments proceeded, and the buckling of the top took so prominent a position, the fears respecting this phenomenon became exaggerated, until the successful result with some of the models with corrugated tops to some extent dissipated these fears, and the tearing away of the sides from the top and the bottom in one of the experiments (hitherto a very unusual kind of failure) excited some apprehensions in this direction, and led to the precautions since taken to obviate such a contingency; but as this was almost a solitary instance of this kind of failure, the investigation of the best kind of cells for the top continued the most prominent object of inquiry. In designing these cells Mr. Stephenson insisted upon the absolute necessity of every portion of the structure being conveniently accessible, in order to paint and examine or repair it, and on this account he decided on the square, rather than the circular, or corrugated, form; the facilities for constructing this form had, moreover, considerable weight in its adoption, all the numerous designs and modifications of the corrugated top being to some extent inaccessible and of complicated construction.

They were therefore discarded, and a model was constructed by the Author, under Mr. Stephenson's directions, in the month of March. This model had a double row of cells at the top and a single row at the bottom.

The bottom area was assumed at 400 square inches, and the top at about 600; these proportions being arrived at from those models in which the top and bottom had appeared about equal in their resistance to transverse strain.

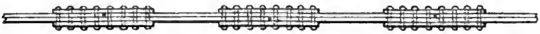
Several sections of tubes with combinations of corrugated plates and circular cells had been proposed; these suggestions had been considered, and the above form appeared best adapted to the requirements of the case.

In considering the details of construction, it was found impossible to unite together in one layer sufficient plates to make up the required sectional area for the bottom; and it was determined, as had been proposed some time previously, to obtain the requisite strength by the construction of cells at the bottom of the tube, as well as at the top; not that the cellular arrangement was supposed to be advantageous in any other way, than as affording the best practical means of putting together the requisite quantity of material, and of affording convenient access for its subsequent examination or repair.

Much practical and other information on this subject had been obtained by observing the method in which fracture had so frequently occurred in the bottoms of the numerous models. In the first experiments, the plates had been simply united by being overlapped, and connected by a double line of rivets; but subsequently, on finding this method of construction very defective, the plates had been united by means of large covers with more numerous rivets. This method of junction was consequently adopted.

It was found impossible, even with the bottom cells as proposed, to obtain plates of sufficient thickness for the sectional area required; and it became, therefore, necessary to use double plates, to unite which effectively involved considerable practical difficulty. The preference given to double plates instead of thick single plates in the construction of the bottom was strengthened from the consideration that the average strength of a number of thin plates may be expected to be more constant than that of a single thickness of the same sectional area, as a faulty plate among so many, like a single broken wire in a wire-rope, would cause but little decrease of strength. It was also considered that surface is, to some extent, connected with the tensile strength of this material.

The following arrangement of the bottom plates was proposed by Mr. Fairbairn:



This species of riveting was subsequently adopted in one of the Conway tubes, and partly in the second; it was also employed in the construction of the greater part of the Britannia Bridge, but was ultimately abandoned for an improvement hereafter described, which not only possesses considerable advantages in facilitating the construction, but obviates the evil occasioned by so many holes occurring in the same transverse section. The empirical formula employed for ascertaining the strength of this design was obtained by the substitution of other constants, in the expression employed by Mr. Hodgkinson for cast-iron beams; these were continually modified according to the results obtained from the various experiments as they progressed, but such calculations were always regarded as mere approximations.

Such was the progress made in April 1846 in the general details and designs, when Mr. Stephenson proposed the construction of the large model so elaborately described hereafter, and which embodied at that time all that had been gained from the experiments: this model was intended to be in every respect a prototype of the eventual bridge, and one-sixth of its lineal dimensions.

During these discussions, which had already occupied much more time than had been originally calculated on, the works on other portions of the Chester and Holyhead Railway were carried on with all possible despatch; and it became evident that these bridges would be ultimately the principal cause of delay in the completion of the line. The Directors became, therefore, naturally impatient that Mr. Stephenson should sufficiently mature his plans to allow of the commencement of the masonry; and with a degree of confidence in his proposals which few shared with them, they instructed him without delay to commence operations simultaneously at both Conway and the Straits, leaving him to complete his designs as he proceeded. This strong testimonial of their confidence in his plans, however gratifying, added considerably to his anxiety. He was naturally most anxious to have awaited the result of the Conway Bridge, which must have furnished valuable experience for the larger structures at the Straits, and to have avoided the weighty responsibility of commencing at the same time two such gigantic structures on principles so novel and untested. It was under these circumstances an important consideration, that the chains, which were intended as a scaffolding for the erection, would be of sufficient strength permanently to support the tubes themselves, should any unforeseen phenomenon arise out of their magnitude, and thus prove an effectual insurance against a ruinous failure. At the same time that the Directors thus urged the commencement of the construction, they did not hesitate, with a liberality characteristic of English enterprise, to sanction the continuance of such further experiments as Mr. Stephenson might deem advisable.

Mr. Thompson, the architect, had been for some time engaged with Mr. Stephenson in preparing designs for the masonry; and he was now instructed to complete his drawings for the foundations, with such an outline of the probable structure as would be sufficient for estimating the requisite quantity of masonry, and for preparing the plans and specifications to lay before the contractors. These provisional plans were ready for the inspection of parties tendering for the contract by the 17th of March, 1846; and on the 10th of April following the first stone in the foundations of the Britannia Bridge was laid by Frank Forster, Esq., the resident engineer for the masonry, and for the whole of that portion of the line extending from near Conway to Holyhead, including the series of stupendous works before described.

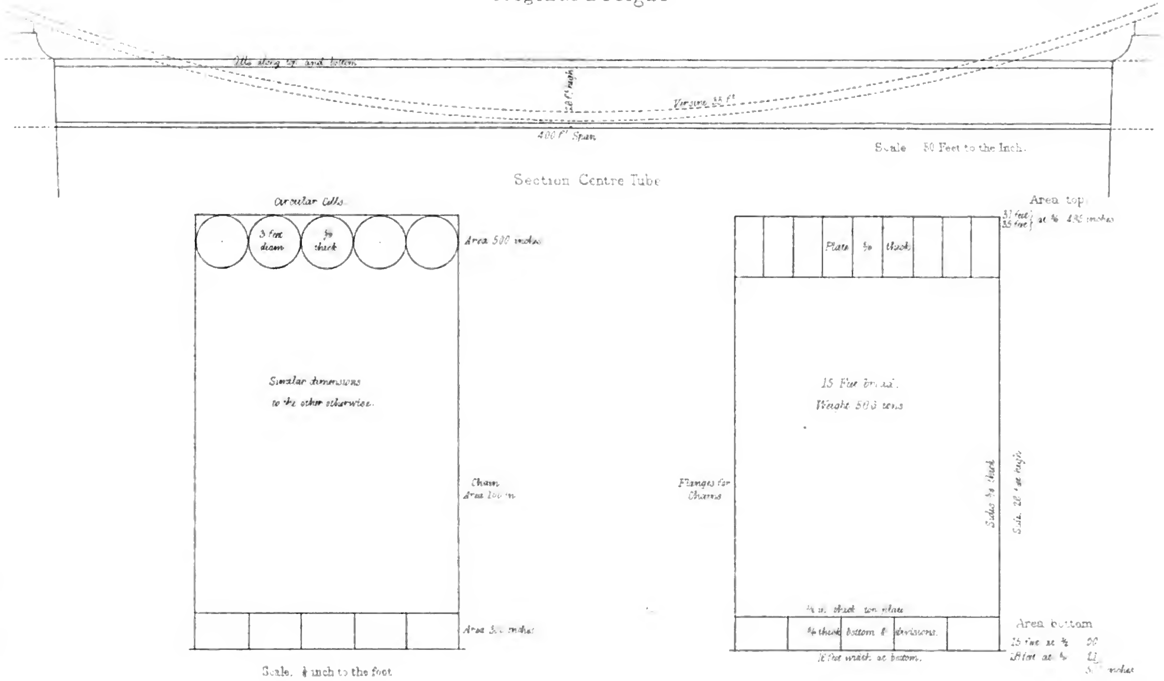
The contract for the masonry was let to Messrs. Nowell, Hemingway, and Pearson, by whom it has been since completed. To these gentlemen no higher compliment can be paid than by quoting Mr. Stephenson's own remarks at the

C O N W A Y B R I D G E

Original Designs

To face P. 433

26th May 1846



placing of the last stone on the top of the Britannia Tower on the 22d of June, 1849:—

> "Mr. Stephenson said, it had fallen to him as a pleasing duty to lay the last stone on the excellent and gigantic work which had been reared by the joint efforts of those around him. He sincerely thanked them for those exertions which had brought it to so successful an issue. No one at first believed it possible that so vast a body of masonry could have been constructed within so short a period. The contractors had spared no expense, wisely judging that early liberality was final economy. Not less that two millions and a half of cubic feet of masonry had been constructed, though three years had not elapsed since the laying of the first stone. The height of the work averaged 100 feet, and the tower upon which they stood peered above the waters 245 feet. The work had gone quietly on with such perseverance that three cubic feet had been accomplished per minute since the commencement, allowing twelve working hours to the day, and six working days in the week. The contractors were entitled to much praise; and he was happy to say that their efforts had not only been successful, but profitable to themselves. If there were any one circumstance more gratifying than another, it was that, from the beginning to the conclusion of this gigantic undertaking, no life had been sacrificed, as was too often the case, from insufficiency of machinery or tackling."

The masonry for the Conway Bridge was almost simultaneously let to Mr. William Evans, who subsequently undertook the construction of the tubes.

The first stone of the Conway Bridge was laid in the north-east angle of the Conway Tower, on the 12th of May, 1846, by A. M. Ross, Esq., under whose experienced superintendence the whole of the line between Chester and Conway was brought to completion.

The accompanying sketch contains the provisional dimensions for the Conway Bridge, as now determined upon, May 26th, 1846. They are extracted from correspondence with Professor Airy, who kindly took great interest in the progress of the design, and not only afforded much valuable assistance by his suggestions, but confirmed with his high authority many of Mr. Stephenson's deductions; his communications being always as remarkable for their elegant and simple treatment of the subject as for the profoundness and practical nature of their remarks.

Similar dimensions were furnished to the architect for the design of the masonry. It was intended to construct this tube on a platform on shore, in a line with and at the level of its permanent site, and to erect simultaneously a suspension-bridge over the Conway River, upon which the tube was to be rolled into its place. With this view designs were completed of the necessary platforms and workshops, as well as of the suspension-bridge, with provision for its ultimate attachment to the tube, if advisable.

Although these plans were not carried out, the original designs for the masonry have been executed without any important alteration. The distance between the two tubes was thus originally regulated by the necessity of having sufficient width between them for two sets of chains.

The following were the details of the intended suspended scaffold:—

Face to face of masonry	400 feet
Centre to centre of suspension..........	415 ,,
Versed sine	35 ,,

CHAINS.

Four to each tube.
Each chain alternately 9 and 10 plates, 1 inch thick.
Each of the 10 plates, 10 inches broad.
Each of the 9 plates, 11$\frac{1}{9}$ inches broad.
Constant area of chain, 100 inches.
Total area of chain for 1 tube, 400 inches.
Length of each link from centre to centre, 12 feet.
Length of each chain, 422·77 feet.

Weight of 4 chains, 372 tons.
Total weight of chains, platform, &c. for 1 tube, 1695 tons.
Maximum tension, everything being supported by the chains, 6·6 tons per square inch.
Angle with the horizon of tangent to the chain at the point of suspension, 71° 12′ 9″.
Tension at the centre of the chain, 6·3 tons per square inch.

The chain was somewhat similar to the one since employed for raising the tubes; the single joint was preferred as being very much lighter than the compound joint frequently used in suspension-bridges.

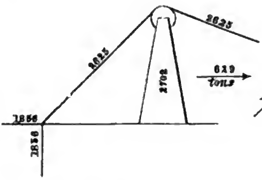
The weight of the joint was still an important addition to the weight of the chain, and on this account the links were designed to be as long as it was possible to construct them without a weld. In the Hungerford Bridge the links are welded, and are 24 feet 6 inches long; but in testing them, some failed at the weld, which, however carefully executed, cannot be depended on.

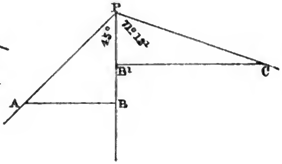
By an ingenious process patented by Messrs. Howard and Ravenhill the welding is rendered unnecessary, the head being rolled simultaneously with the shaft, and in this manner the chains for raising the tubes were subsequently manufactured. The process is as follows:—The "Blooms," or fagots of carefully-piled scrap-iron, prepared under the tilt-hammer for rolling, were (in the case of the lifting-chains) about 2 feet long and 7 inches square. These were, by the ordinary process of rolling, reduced to plates of about half the length of the intended link (half of 6 feet), the breadth of 7 inches remaining unaltered. The plates were next passed sideways between rollers with their centre portions turned away; so that the ends only of the plate, which were to form the heads of the link, were rolled out, the centre preserving its original thickness. In this form the link was again passed longitudinally through ordinary rollers, where the centre portion only coming in contact with the rollers, was brought to the required length and thickness.

The chains, as before mentioned, were to be first secured to the rock on either side, and afterwards to the tube itself, if extra support should be found necessary; and they would then pass over movable saddles on each tower, descending from the tower to the rock at an angle of 45°.*

---

* There are two methods of supporting the chain of a suspension-bridge. 1. It may pass over a drum fixed in the tower. In this case the chain being continuous, it is evident that the tensions on each side of the drum will be equal, and the horizontal forces will only balance each other when the chain makes equal angles on each side. In other positions there will be a horizontal force tending to overthrow the tower. As an example, in our case we have





$\angle APB = 45°$. $\angle BPC = 71° 12'$. PC or PA = 2625 tons.

Now $\frac{B'C}{PC} = \sin 71° 12' = {\cdot}9466$

$\therefore B'C = PC \times {\cdot}9466$

$= 2625 \text{ tons} \times {\cdot}9466 \qquad = 2485 \text{ tons.}$

Similarly $AB = AP \times \sin 45°$

$= 2625 \text{ tons} \times {\cdot}7071 \qquad = 1856 \text{ tons.}$

Difference, or pull, on lower to the right $\qquad = 629$ tons.

Also vertically $PB = \cos 45° \times 2625 \text{ tons} \qquad = 1856$ tons.

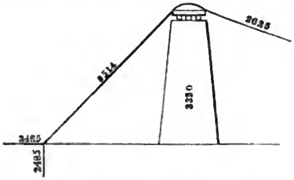
And $PB' = \cos 71° 12' \times 2625 \text{ tons} \qquad = 846$,,

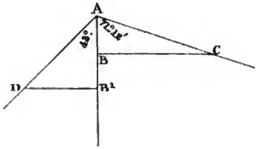
Total vertical pressure $\qquad = 2702$ tons.

2. As is usual in most large suspension-bridges, the chain may be attached to a movable saddle or to the axis of a roller, free to move horizontally.

The saddle intended for the Conway Bridge was movable on rollers, six inches in diameter, in the tower, as in the Hungerford Bridge ; and to obviate the effects of expansion,

The saddle in this case being at liberty to move, will rest only where the horizontal forces balance each other ; consequently, there will be no stress tending to overturn the tower, but the tensions on either side will vary with the angle made by the chain with the tower, and will only be equal when those angles are equal. To exemplify this in our present case,—





Since A is kept in equilibrium by the horizontal forces on each side, those forces must be equal.

To the right we have $\frac{BC}{AC} = \sin BAC$

Therefore $BC = AC \times \sin BAC$

To the left similarly $DB' = AD \times \sin DAB'$

Therefore $AD \times \sin DAB' = AC \times \sin BAC$

Or $AD = \frac{AC \times \sin BAC}{\sin DAB'}$

$$= \frac{2625 \text{ tons} \times {\cdot}9466}{{\cdot}7071} = 3514 \text{ tons.}$$

In the same manner we find the vertical pressure to be 3330 tons, and resolving the strain on A D into its horizontal and vertical effects, we should find them each equal to 2485 tons.

The chain A D must thus be stronger than the main chain in the proportion of 3514 to 2625, or 1·338 to 1.

In many of the Continental suspension-bridges the chain is attached to the top of the pier instead of resting on movable rollers, in which case, also, there is no horizontal force, provided there is no expansion and contraction in the chain. The tension on A D is then precisely the same as in the last case, the only difference being that with the movable rollers the pressure is rendered perfectly vertical by self-adjustment, while in this case it is ensured by the original adjustment of the chain.

and to ensure the nearly constant action of the chain in supporting the tube, if it had been found advisable to connect them permanently, the chain would have been attached to the tube, as before described, the vertical strain being entirely resisted by a link attached at the bottom of a shaft, excavated in the rock for that purpose.

The strains indicated in the figures in the note will explain this action of compensation; they are calculated on the supposition of the chain supporting the whole weight of the tube, which in practice would not have occurred.

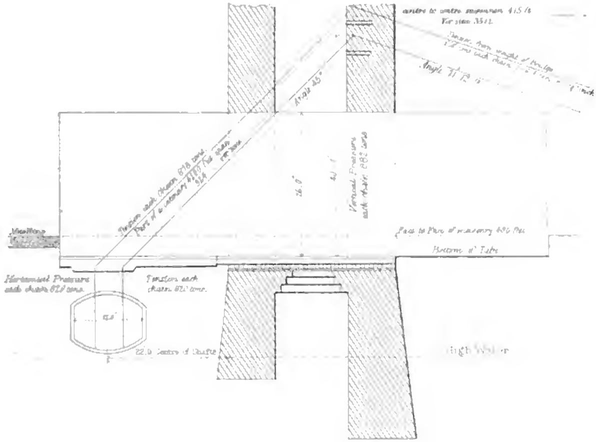
The tie-chains may be taken as straight lines, for they would be portions of a catenary of about 4200 feet span and 924 feet versed sine; the main-chains having 400 inches of sectional area, the tie-chains would have required 535 inches of section.

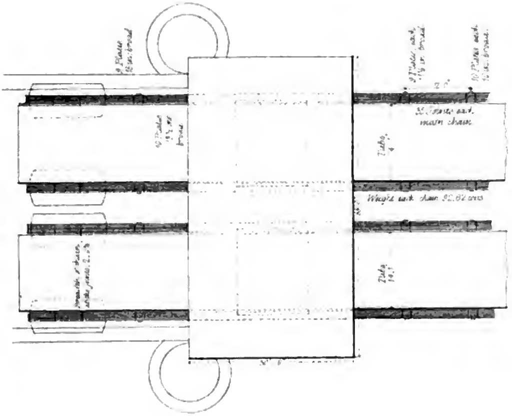
As the tubes of the Britannia Bridge, when in place, were to be connected, in order to form one continuous tube, the chains would have been secured over the centre tower, and the saddles would have been at liberty to move on the side towers and abutments only. It was proposed to support the saddles by means of a cast-iron framing over each of the towers, and ultimately to attach these frames to the tube itself. In this manner the tubes, saddles, and chains, would have formed a complete independent system, merely resting vertically on rollers over the towers, the chains at either end being attached to the tubes.

In designing these suspension-bridges considerable assistance was derived from particulars of Hungerford Bridge, and the intended bridge at Clifton, kindly furnished by Mr. Brunel, and from details of Hammersmith Bridge, and of the chains of the Pesth Bridge, obligingly communicated by Mr. Tierney Clark.

An etching of the intended bridge at the Straits, embodying these views, was printed by the architect in May 1846;

PROPOSED ATTACHMENT OF CHAINS, CONWAY BRIDGE.


centre to centre suspension 415 ft
Ver sine 35 ft
Tension from weight of bridge 172 tons each chain
Angle 71 12
Angle 45°
Tension each chain 818 tons
Part of a catenary 4180 ft span
924
76 tons
16.0
40.0
Vertical Pressure each chain 282 tons
Pass to Pier of masonry 696 ft
Bottom of Tube
Horizontal Pressure each chain 821 tons
Tension each chain 821 tons
12.0
22.0 Centre of Shafts
High Water


9 Plates 18 in. broad
9 Plates each 18 in. broad
10 Plates each 18 in. broad
2.0
10 Plates 18 in. broad
35 Plates each main chain
Tube
Weight each chain 92.82 tons
Tube 14.3
Section of chain shewing joints
30.0

Day & Son, Lith^rs to the Queen.

a model of the suspension-bridge, in connexion with the tube, was also prepared by the Author, under Mr. Stephenson's directions, and drawings of the more important parts of the detail were completed. The months of May and June, and part of July, were devoted to these inquiries, and in the meantime considerable progress was made with the foundations of both the bridges. The tube itself was also gradually progressing in detail, but maintaining its original general outline; the celebrated problems of the wind and of vibration continued to occupy some attention in theory, while in practice the stiffening of the sides and the top were the most important questions. Circular cells at the angles were suggested by some friends, while others proposed to make the tube perfectly square in section, with double sides. Some advocated sheets or rods across the angles, to assist in preserving the form; and others, deep vertical plates in the top, to increase its longitudinal rigidity.

Mr. Fairbairn suggested a wooden top outside as an auxiliary to the top plates in resisting a crushing force, and as a muffle, in conjunction with vulcanised Indian-rubber beneath the rails, to the rattling canister sound which he apprehended.

All these suggestions, as well as others of a more theoretical character, were submitted to Mr. Stephenson, and carefully considered in the daily discussions on the subject. His views on some of these subjects are thus recorded in an official communication to Mr. Fairbairn by the Author:—

"24 Great George Street, Westminster,
"24th June, 1846.

"Dear Sir,

"I beg to communicate the result of an interview with Mr. Stephenson on the subject of the Conway. * * * * He requests me to add, that he has been considering your suggestions as to the chains, and your proposed section of tube.

With respect to the upper part of the tube, there does not occur any reason why the upper cells should be 30 inches deep, and the next series 20. The reverse would rather appear advisable, viz. to make the upper cells 20, and the lower 30, which would throw the strength near the top, where most wanted; or, at any rate, he proposes, for the convenience of repair, &c., that the two series be each of the same size, viz. each 25 inches deep. He also appears to have some objections to the proposed caulked top, which will materially increase both the weight and expense of the tube without the slightest increase of strength, or any other important advantage. Moreover, the oval rings of T-iron, proposed to be inserted in the bottom cells, do not appear to be of any service; in other respects, it appears to be of proper dimensions. I have calculated the area as follows:

"Top cells, 469 square inches; corner irons, 178; total, 647. Bottom cells, 294; corner irons, 112; total, 406.

"A slight increase is necessary in the area of the top. The lower horizontal plate at top might be half-an-inch, instead of three-eighths, as I have taken it, which would give 668 area at top. The deduction from experiments would require 678.

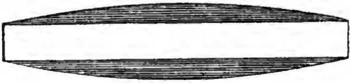
"It is necessary that the corner-irons along the bottom should be continuously connected throughout the tube.

"With respect to the chains, Mr. Stephenson would prefer the simple joint (as in my tracing), to the compound joint, proposed in your sketch. The principal objections are, the great additional weight of such joints without any increase of strength, and the much greater amount of work, and consequently expense, in their manufacture.

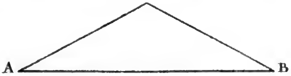
"The length of the links must, of course, be altered to suit the limits of practicability; which, for the present, it appears, may be assumed as 12 feet, according to your inquiries."

A subject which occupied Mr. Stephenson's attention during this period, was the advantage to be obtained from the continuity of the tube at the Britannia Bridge, by the union of all the tubes into one.

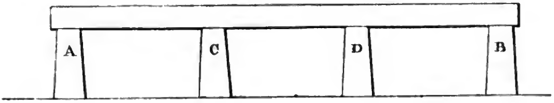
In an ordinary beam the strain is greatest at the centre, and decreases towards either end, in proportion to the product of the distances of any point from either end; the top as well as the bottom would thus require to be of greatest section in the centre, and to be diminished in strength in the above proportion towards either extremity, otherwise the beam would be loaded with an unnecessary weight at the ends. If in the following figure we suppose the shaded distance between the lines to represent the thickness of the top and bottom of a tube, each composed of a single plate, we shall form some notion of the requisite variation in thickness.



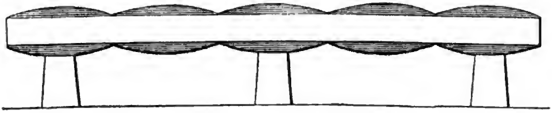
And it is in this respect that a beam differs so widely from an ordinary trussed roof, where the tie-rod *a*, *b*,

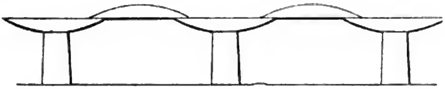


connected with the rafters at *a* and *b*, suffers an equal extension along its whole length, while the rafters similarly sustain an equal thrust throughout, and, consequently, the sectional area, both of the tie-rod and rafters, would be constant throughout. The strain at the centre of the beam may be considered as the sum of an infinite series of strains throughout the top and bottom, originating from the diagonal strain through the sides, the strain in the top or bottom at the extremities being nothing. But if the tube A, B, in the figure below is constructed in one piece before it is placed on

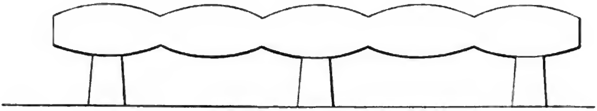


the towers A, C, D, B, there will then be, from the deflection of the tube, a strain over the towers at C and D, which will relieve the strain at the centre, so that the tube might be cut in two at the middle of the centre span without falling; it is evident, then, that the thickness of the plates in the top and bottom would follow a different law, would require to be differently proportioned to be adapted to these circumstances, and instead of tapering off to nothing over the towers the greatest strength would be required there. The top of the tube would no longer be wholly in a state of compression, as before, but some portion of it near to the tower would be in a state of tension, while there would be a neutral point, at some distance from the tower, without either extension or compression; the tube would consequently be proportionately increased in strength, and if merely strong enough, as a single beam, to support its own weight, it may thus be enabled to bear a considerable additional load. The thickness required in the plates for the top and bottom would now vary somewhat as in the following figure, and the tube becomes analogous to a shorter tube resting on brackets from the pier at either extremity, as below.

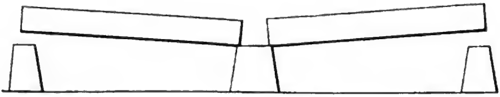




Now the strength of the Conway Bridge is made greater at the centre, not merely by increasing the thickness of the plates, but partly by increasing the depth, the top having an arched form for that purpose; and if the strength in the continuous tube were to be similarly partly varied by an alteration of depth, the following figure would more resemble the side elevation.



It was, however, impracticable to construct the Britannia Tubes in one entire length, previous to their taking their deflection from their own weight, under which circumstances the union in the towers would give no assistance in supporting the tube itself. To remedy this result, it was proposed that, previous to joining the large tubes in the centre tower, each opposite extremity should be raised above its permanent bed, and in this state that the tubes should be united, as in the following figure.



It is thus evident, that on lowering the extremities the requisite strain over the centre tower will be obtained, and the tube will possess the same advantages from continuity as though it had been constructed in one entire length previous to being placed in its position. This became of more importance when it was decided to raise the tubes entire without a suspension-bridge, and has since been successfully accomplished.

The calculated strength was always made sufficient by Mr. Stephenson without this addition from continuity, and had reference solely to the bottom, there being no data for determining the strength of the top, which was roughly ascertained from the models with thin plates.

CHAPTER II.

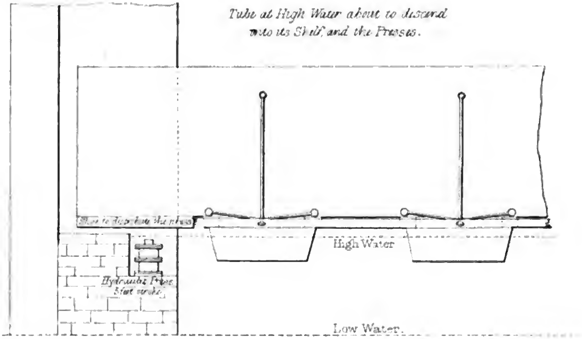
PROPOSAL FOR FLOATING AND RAISING THE TUBES.

July 1846 to May 1847.

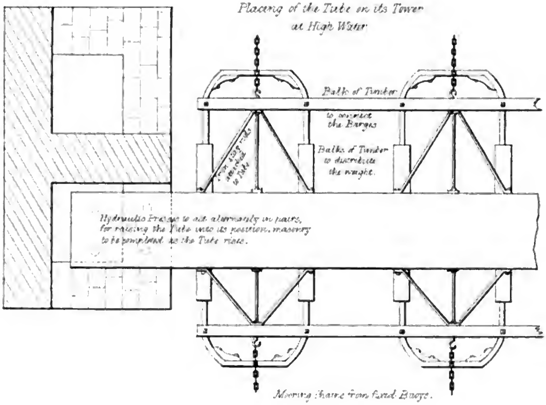
An important change took place in the proposed method of erecting the tubes, which naturally separates the following history of the bridges into another epoch.

It will be remembered that the idea of floating the cast-iron arch for the Conway Bridge on a series of pontoons had been one of Mr. Stephenson's first suggestions for erecting that structure. This plan was, however, discarded, for the reasons explained by him; and during its consideration the many difficulties to be encountered had been fully discussed. Such an operation was totally inapplicable for the proposed cast-iron arch at the Straits. When, however, the arch was superseded by the tube in both localities, this method of placing the tube in its place at Conway was again discussed; the form which the bridge had now assumed was evidently peculiarly favourable for such an operation, as the necessity for the massive timber platform requisite for the arch was obviated; and instead of so bulky a raft, extending the whole length of the structure, barges or pontoons at each extremity only would be sufficient. It was, therefore, proposed to construct the tubes on the beach, and thence float them to their ultimate position. The success of this operation evidently presupposed sufficient strength in the bridge independent of chains; but Mr. Stephenson considered that the valuable insurance afforded by chains against any accident which might occur from unforeseen causes, to be a consideration of vital importance; and he did not feel justified, in the then state of his information with respect to such structures, in throwing away the chance of such undoubted security. He was also the more anxious, as he was not able to await the result of the experiment on the Conway Tube, but was compelled to proceed simultaneously, and without delay, with two such important structures on such contested principles. He had determined, therefore, to employ the suspended scaffold, not only as an equally eligible method of placing the tubes in place, but as an insurance, and not a very heavy one, compared with the cost of the bridge, against any possibility of accident. The economy of employing the same process and the same tackle for two bridges so similar, and so near together, was another argument against any modification. As it became more and more evident, on further consideration, that little danger was to be apprehended from the size of the tubes, and the completed estimates for the suspension-bridge with the then high price of wrought-iron were very large, the subject was again discussed; and on the 14th of July, while under consideration, the Author was sent by Mr. Stephenson to Manchester; in stopping at the Crewe station he was struck with the process by which the contractors were raising a small water-tank, for some temporary purpose. This tank was being raised in a recess, by means of screw-jacks resting on a base in the recess, the tank being blocked up at the end of each lift by packings placed beneath it while the jacks were lowered back, and similar packing placed beneath them for another lift. This led at once to the idea that similar machinery on a larger scale might be available for raising the Conway Tubes. The tubes might be placed in recesses purposely constructed in the towers for that purpose. An hydraulic press of proper

FIRST PROPOSITION FOR FLOATING AND RAISING THE CONWAY BRIDGE.



Tube at High Water about to descend into its Shelf and the Presses.



Placing of the Tube on its Tower at High Water

Balk of Timber
to connect
the Barges
Balks of Timber
to distribute
the weight.
Iron stay rods
attached
to Tube
Hydraulic Presses to act alternately in pairs,
for raising the Tube into its position, masonry
to be completed as the Tube rises.
Mooring chains from fixed Buoys.

Day & Son, lith.rs to the Queen

dimensions might take the place of the screw-jacks, and the tube be followed up from beneath by brickwork as it ascended simultaneously with the presses. The Author was at once strongly impressed with the feasibility of this idea, though, knowing the decided objections of Mr. Stephenson to floating, which would now be indispensable, he had little hopes of inducing him to change his plans; he, however, proceeded, on the morning of the 15th, to make sketches of the general principles of the suggestion, and to describe them, first, to Mr. Fairbairn's assistant, Mr. Blair, and in the course of the day, in his presence, to Mr. Fairbairn himself, requesting him to give him his assistance in overcoming Mr. Stephenson's scruples. He was convinced of the advantages that were apprehended, and by the same day's post forwarded a letter to Mr. Stephenson, describing the suggestion and advocating the principle.

The accompanying plate is a representation, on a reduced scale, of the first sketches above alluded to.

Mr. Stephenson gave this proposition his consideration, his original objections to floating the tubes will be seen in his reply:—

> "I should be delighted to get away, but there are two or three Boards of Directors who threaten me with actions for damages if I absent myself from London, now that they have got their committees in the Lords' appointed.
>
> "I received your letter from Newcastle, and have turned over your proposal for another mode of erection, but the same plan was discussed at some length by myself and Mr. Ross for the Conway Bridge. I proposed three pontoons upon which to place the tube, and then to float it into its place exactly as proposed in your letter.
>
> "After much consideration I felt that, although practicable, the risk of accident was so great, and the consequence of any miscarriage so serious, that I abandoned it, and resorted to the chains. The tidal current, both at the Conway and at the Menai Straits, is very rapid,

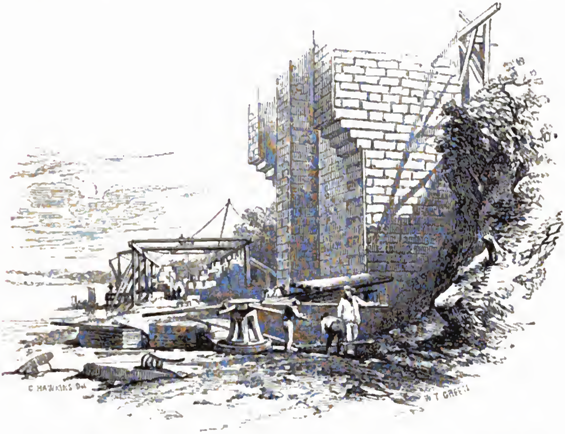
and would render the management of such a mass as a tube and pontoons extremely difficult and precarious.

"Under these impressions I was led to adhere to the safest method notwithstanding the expense. In such an undertaking I do not feel justified in running the least risk; but I am still ready to re-discuss the plan with you, and if I can see my way clearly I shall not hesitate to modify my present views.

"The objection which first occurred to me in the plan of raising the tube, simultaneously with the masonry, was the delay which would take place with the masonry, because it is evident that we must stop proceedings at once until the tubes are all completely finished. The tubes in this case would no doubt be useful auxiliaries for raising the stonework, but they, on the other hand, would much embarrass the process of setting. These, however, are not objections to the principle, and, if safety can be attained, ought not to weigh at all. Now, as to getting down to Manchester this week, I am afraid it is wholly impracticable, for I have three Bills in the Lords', which I did not expect to come on so soon, and I dare not be seen in spite of the doctor, who is insisting upon my leaving town for some days, in order to get some *quietness*.

"If, therefore, you and Mr. Clark deem it essential to see me, I am under the necessity of asking you to come to town."

As the subject of floating came to be discussed, many modifications of the original proposal naturally suggested themselves. The subject was carefully re-considered by Mr. Stephenson, the proposal was adopted, and the necessary instructions were given to Mr. Thompson, Mr. Forster, and Mr. Ross, to prepare the masonry accordingly. The progress that had been made did not, fortunately, much interfere with the alteration. It was decided that the recesses should be 15 feet 4 inches wide, and 6 feet deep, at the level of the tubes, and that the face should be smooth ashlar work, to offer no obstruction to the tube as it was being raised. On account of the batter in the tower the depth of the recesses at the bottom would then be 10 feet; the outside walls of the recesses were settled at 8 feet broad, and the centre buttress at 8 feet 4 inches. These buttresses were corbelled over at the base to admit the tubes, as in the following vignette, which represents the corbelling of the Carnarvon Tower. The object of these recesses was, 1st, To ensure



a vertical pull over the tubes for the purpose of raising them up the grooves; and 2dly, to secure the tubes from lateral motion, caused by the wind, so that at every part of their ascent they would be firmly secured in the solid masonry of the towers. It was proposed to remove the tubes from the platforms into these recesses by means of barges placed between the piles of the platform, and thus to float them with the rising tide. As the tube was raised up the recess, it was to be blocked up beneath with cast-iron frames or pillars, secured to the back and sides of the recess, for which purpose holes were ordered to be left in the masonry, but brickwork was ultimately adopted for this purpose. A plan of the Straits, and of the River Conway in the neighbourhood of the bridge, was also prepared to assist in determining the best site for the construction of the tubes; and on the 11th of August the Author proceeded, in company with Captain Moorsom, R.N., Mr. Frank Forster, and Mr. Fairbairn, to make the necessary local arrangements for commencing the work, and to select a site for the workshops and platforms.

The nature of the locality will be seen from the Report to Mr. Stephenson on the subject:—

"George Hotel, Menai Straits,
"13th August, 1846.

"The rocky and inhospitable coast in all directions gave us some difficulty in selecting a proper site for the intended wharf and shed, and in fact no very favourable spot is within reach. The Carnarvon side may probably best suit our purpose.

"On account of the impossibility of passing under the Conway suspension-bridge, the wharf for that bridge must be on the further side, so that one set of shops cannot be available for both bridges.

"No stones are at present laid at the Britannia, but a large stock is prepared; they are waiting for the altered plans, which should be prepared by Mr. Thompson, and forwarded as speedily as possible, as it appears it will make a considerable difference in their preparation of the stones.

"It is a fearful span when looking at it on the spot. I do not know how the span was measured, but I presume trigonometrically. It appears to me the most accurate plan would be to suspend a surveying chain, or a similar chain, from a determined height across the water, to touch it in the centre, thus knowing the length of the catenary and the versed sine, the span would be exactly determined.

"Mr. Fairbairn will proceed to Manchester on Saturday, and as soon as you leave he says he shall want me with him to get up wharfs, &c. It is also, I presume, necessary that I should explain the intended alterations to Mr. Thompson.

"Will you be so kind as to let me know your wishes with regard to my proceedings?

"Edwin Clark."

Mr. Stephenson decided that the site since adopted on the Carnarvon shore, as shewn in Plate I., would be the most convenient for the construction of the tubes. At the spot in question a belt of exposed rock, between the ordinary high and low-water lines, averaging about ninety feet in breadth, and long enough for the construction of the four tubes end to end, was selected. About midway between high and low-water mark it was proposed to erect the platform for putting together the tubes, at such a height above the level of high-water as to be out of the reach of the tide, and so that barges, or pontoons, might, with little excavation, be floated underneath each tube for the purpose of removing it. It was discussed whether rough masonry, or timber framing, would be most economical for the range of piers, and ultimately the present timber platform was decided on.

At Conway a similar belt of rock was selected south of the bridge, as in Plate XXXIV.

The two following reports to Mr. Stephenson will explain the ultimate arrangements both at Conway and the Straits :—

"Menai Straits, 11th January, 1847.

"Dear Sir,

"Mr. Forster and myself have definitely staked out the site for the platform here, and very little excavation will be necessary. We have kept as far out as the navigation will allow, and the end of the platform nearest the bridge comes very close to the tower at the foot of the road leading down to the beach. There will be a landing-pier at this spot, and also at the further end of the second platform, the ground not allowing the proposed dock between the two.

"The top of the platform will be just level with higher water spring-tide, the bottom of the tube being blocked up three feet above high-water. When these blocks are removed, it leaves abundance of latitude for lowering the tube on to the boats without chance of fouling. The timber will be uninjured by the proposed method of framing it, and about twenty transverse sets of frames will be sufficient. I am remaining here till to-morrow, to complete the drawings at Forster's office before I leave, so that the estimates will be ready in three or four days, both for platforms and houses for the men, and they can be commenced as soon as you like. In fact, a portion to begin putting the tube together could be ready in three weeks if required, and the whole in about two months.

"The masonry gets on rapidly. The abutments on the Anglesey side resemble the foundations of some great city, rather than a single structure, and nothing appears to stand still here.

"I will proceed from here to Conway to make similar arrangements there, and will then take the drawings to Mr. Fairbairn for his inspection, and go there into the question of the top; but I presume it will be better to have some further consultation with you on that subject before definitely settling it, and I will bring tracings to London for that purpose. In the meantime I will also procure estimates for the large boats, and shall be prepared to draw up a report to lay before the Finance Committee, according to your desire, immediately I return."

"Manchester, 15th January, 1847.

"My dear Sir,

"I remained two days with Evans, and nothing can be more satisfactory than his progress in every respect. Mr. Ross met me at Conway according to appointment, and, together, we settled every matter that was at all pressing. About one hundred tons of plates are waiting at Runcorn, and will be at Conway in a few days. His 20-horse engine, and three presses for punching, his large workshops, and scaffolding around the platform, and all his plant, are on the ground, and indeed nearly all put up, so that he really will begin in a few days, with every chance of making good progress.

"I finished drawings there of the platforms, which he will comply with in every respect. I also made the necessary alterations in the masonry drawings, agreeing, as at the Britannia, to complete the counterforts of one tower, leaving the corbelling only in the other: this will now be proceeded with.

"Evans was about to build four large barges for himself, and we have agreed to use them also at the Straits, on such terms as you may name, provided he made them according to our plans: this of course he agreed to, and I made drawings there for him. He was proposing several objectionable details, which he alters most willingly, and the boats will be begun to-morrow, 95 feet long, 25 broad, 8 feet deep, drawing 6 feet loaded. I left with him directions as to the masonry at the ends of the tube for raising it off the platform, with drawings, which he will at once work to.

"I have procured estimates, according to your directions, of every matter, and shall be prepared to submit them on my return to the Finance Committee, with the necessary description.

"I have described to Mr. Fairbairn all the matters which I have settled.

"I will go into the top here, and return to London next week.

"E. Clark."

Mr. Stephenson was at first inclined to use smaller pontoons. He observes in a letter,—

"November 1846.

"I have been constantly canvassing and calculating the stability of the barges lengthwise since I left you, without having arrived at any very satisfactory result. The great height of the tube, and the position of the centre of gravity, render the use of short barges very precarious; but with long ones the difficulty does not entirely disappear, at least another starts up, although I do not deem it so formidable as the strength of framing and trussing which long barges must necessarily require to prevent their breaking in the middle. In any case I have a strong leaning to the employment of a considerable number of vessels, instead of a small number, for with a large number a casualty to any one or two of them would not much interfere with our proceedings or progress during the floating; this, I think, you will agree with me, is of the very last importance—some contingency we must encounter."

In accordance with these views inquiries were made at Bristol, Gloucester, and Liverpool, to ascertain whether there was any probability of being able to purchase a sufficient number of the flats or other craft employed in these ports, should they prove applicable to the purpose. The quantity of trussing requisite for sufficiently strengthening these vessels, their great draught of water, and their high price, made it apparent that it would be better policy to construct special pontoons for the service, and of larger dimensions. See Plate XXV.

It was calculated that the four pontoons would draw 6 feet water when supporting their load. The longitudinal balks, on which the tube was to rest, were to be American elm, the rest of the timber being good red pine, with 3-inch planking throughout.

It was suggested by some friends, that by stopping up the ends of the tube it might be floated to its position without pontoons; but even supposing that the numberless joints could have been made water-tight, the draught of water would have been nearly 6 feet, and very extensive excavations would have been requisite at the base of the piers. Other circumstances also render such a proposal impracticable.

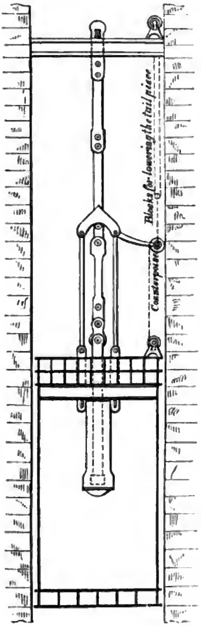
The detailed arrangements for the floating and raising have been considerably modified since their first proposal; but the main features are unaltered. The removal of the press from beneath the tube to the top of the towers rendered the wall-boxes requisite in the buttresses; and among other advantages in this position of the presses was, the facility afforded for introducing the girders into these wall-boxes, and the adjustment of the bed-plates beneath the tubes. The proper junction of the tubes end to end was also much facilitated.

DESIGN OF THE HYDRAULIC PRESSES.

The first suggestion with respect to the presses was to place them beneath the tube at either end within the recesses, which would prevent any possibility of the tube falling over sideways, and after making a complete stroke with the ram to under-build the tube in its raised position, or to prop it up with cast-iron frames; the ram being then withdrawn into the cylinder, the presses themselves might be raised on similar frames, and the operation repeated. To facilitate the raising of the press, it was next proposed to invert it, and attach it to the bottom of the tube, so that the ram, re-acting against the masonry, would thus raise both the press and the tube. This would require two sets of cast-iron frames; the one for the support of the tube, and the other for the support of the press. To remedy the inconvenience of introducing these frames piecemeal throughout a height of 100 feet, a plan was proposed, as described in the following extract from a letter written by the Author to Mr. Fairbairn, in August 1846, viz.:—

> "To use only one set of frames for supporting the tube, and to use the tube as a scaffold for their movements, by means of a rail on the top, so that they could be hoisted out of the boats, and be always ready to run into their places as soon as the tube is raised.
>
> "The pumps would then be placed on the top of the buttresses, which would be undamaged by any holes for scaffolding; and the shortening of the chains at each stroke of the pumps could be accomplished by using a chain of plates similar to a suspension-bridge chain with 10-feet links, with a cramp to seize them below the expansion at the eye of every joint, and thus take off the top set of links, and lower the piston to lay hold of the next set at every stroke."

The next modification proposed was to place the presses inside the tube; the ram passing through the top of the tube was to be attached to chains suspended from girders at the top of the tower across the recesses, as in the annexed figure.



By this process the necessity for frames or brickwork beneath the tube was obviated; for, as will be seen in the figure, there was a clamping apparatus attached to the top of the tube in such a manner that when the tube was raised by the descent of the ram the whole length of the stroke, this clamping apparatus was attached to the links of the chain by means of an extra pin through the chain for that purpose; and in this position the tube was securely suspended until the lower link was removed, and the ram again raised and attached to repeat the process.

The diameter of the ram, which was now a wrought-iron suspension-rod, was twelve inches, the diameter of the press being twenty-one. The practical power of the press at 3 tons per circular inch was therefore $(21^2 - 12^2) \times 3 = 891$ tons, the weight to be raised being then taken at 1200 tons, or 600 to each press, the area of the chain, at 5 tons per inch, was 120 square inches, which it was proposed should consist of twelve plates ten inches broad, and one inch thick.

Messrs. Easton and Amos, of the Grove Iron Works, Southwark, were appointed by Mr. Stephenson to construct the presses, and to complete the design, which they have since so successfully accomplished.

The first drawing made by Messrs. Easton and Amos was a completion of the press as last described for the interior of the tube.

The best method of working the force-pumps was next considered. It had been first proposed to work them by hand, applying handles similar to those used in fire-engines in the interior of the tube. This, although perfectly practicable, was superseded on account of the risk, in case of any accident, which so many men would incur; the requisite machinery for working the pumps was also rather intricate and expensive. It was therefore preferred to employ a steam-engine for that purpose, placed on the top of the tube. The diameter of the force-pump first proposed was an inch and three-quarters, the area of the piston being 2·405 square inches. Three tons per circular inch, or 8556 lbs. per square inch, being the usual pressure to which hydraulic presses are subjected, the required dimensions of the steam cylinder are found as follows:

$(2{\cdot}405 \times 8556) + \frac{1}{3}$ (the usual allowance for friction and waste of powers) gives 27,436 lbs. pressure on the piston of the steam cylinder; and assuming 50 lbs. per square inch as the pressure of the steam, the required area of the steam piston, supposing it to make the same number of strokes per minute as the pump, would be—

$$\frac{27436}{50} = 548 \text{ square inches.}$$

With respect to the velocity for the motion of the ram, assuming two pumps at 40 strokes per minute, and the length of the stroke of the pump being 12 inches, the area of the pump being 2·405 square inches, and of the ram 233·27 inches, we have—

$$\frac{40 \times 12 \times 2{\cdot}405 \times 2}{233{\cdot}27} = 9 \text{ inches per minute for the velocity of the ram.}$$

These dimensions, it will be found hereafter, were but slightly modified; but on subsequent consideration the method of application of the presses was considerably altered. The principal advantages proposed in placing the presses inside the tubes were, that the large gap necessary in the masonry at the top of the towers was avoided; the danger of instability, and the necessity for the guide-rods, was superseded; the raising and fixing of the presses in the towers was avoided, and the quantity of cast-iron work considerably diminished. These advantages were, however, counterbalanced by the practical difficulty of constructing such a press, five leather collars being required instead of one, and the diameter being also much increased. It was accordingly decided, that the presses should be built in the recesses at the top of the towers.

Some advantages suggested themselves in the use of two presses at each end, with a single chain from the centre of the cross-head. Some difficulty was, however, apprehended in preserving the cross-head horizontal; and in case of failure of either of the pair, the tube would be thrown sideways, and probably destroyed.* The single chain would, moreover, have been a very unwieldy affair. Mr. Fairbairn was inclined to recommend the use of double presses; and the following letter to that gentleman will explain Mr. Stephenson's motives for preferring the single cylinder :—

"24th April, 1847.

"MY DEAR SIR,

"Easton and Amos have completed the drawings both for one press and two presses; and besides the difficulty of working two presses simultaneously, there were several other objections in the detail of so important a nature, that, in spite of the extra expense in chains, Mr. Stephenson at once determined on using only one press, and desired me not to leave London until I had definitely settled the matter,—which I have done. Tracings of the presses will be sent you as soon as they can be copied; and Easton is proceeding with them immediately. Drawings of the necessary chains as altered have also been furnished to Howard and Ravenhill for them to lose no time.

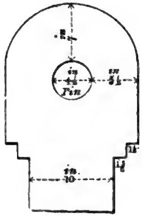
---

* In raising the Britannia Bridge with a double press at one end, and a single press at the other, the single press suddenly gave way, and the tube descended vertically on to the packings beneath it. Had one of the double presses failed, the consequences would probably have been much more serious.

"E. Clark."

The presses and chains are evidently so immediately connected, that they were designed simultaneously.

In June 1846, when it was proposed to use chains in the suspended scaffold for the erection of the bridge, application had been made to Messrs. Howard and Ravenhill, to consult them on the subject of their construction. The Author again put himself in communication with those gentlemen who were at that time engaged in rolling the highly-finished links intended by Mr. Tierney Clark for the bridge he was then constructing at Pesth. As a means of securing these chains, for the purpose of raising them, Mr. Tierney Clark had adopted a most ingenious mode of clamping them by slotting steps in the head of the link. The annexed figure represents the head of the links then in course of construction for him at the above works.



This process of gripping the chain at once suggested itself as much more simple than the rather complicated clamping apparatus described at page 506. It was accordingly decided by Mr. Stephenson to order a nearly similar link for the raising of the Conway Bridge, using wrought-iron clamping cheeks, as in Plate XXVIII. for the support of the tube.

The links were rolled without a weld by the process patented by Messrs. Howard and Ravenhill; and their construction was intrusted to these gentlemen. In obtaining the best proportion for the pins, the Author had the benefit of some valuable information from Mr. Tierney Clark, and from details of the Hungerford Bridge kindly furnished by Mr. Brunel.

The ingenious manner in which the clamping machinery was completed and successfully used, and the admirable accuracy of workmanship with which the chains were executed, to ensure the equal bearing of each link, will be described hereafter.

As the weight of the tube at the time this machinery was designed was much under-estimated, it was found necessary, in raising the Britannia Bridge in 1849, to make many important alterations; and as it was feared that the strain would be rather too great for the two small presses used at Conway, it was decided to use these two presses for one end only of the tube, and to construct a separate and rather larger press for the other extremity. It will be seen hereafter that this new press failed, with fatal consequences, on account of the peculiar formation of the bottom.

CHAPTER III.

COMPLETION OF THE DESIGN FOR THE TUBES.

July 1846 to May 1847.

As the Directors became extremely anxious for the commencement of the iron-work of the bridges, Mr. Stephenson was compelled, without awaiting the result of further inquiries, to proceed with the completion of the designs sufficient for the letting of the contracts. His position is thus expressed to Mr. Hodgkinson:—

> "The Directors are pledged to the shareholders to have this portion of the line open by a certain period: and I am bound, even at the risk of not having arrived at the very best mode of distributing the material in the tube, to proceed: for the consequence of delay, in a commercial point of view, after upwards of a million of money has been spent in finishing the works, is not simply the interest, but the loss of income; and those together, you will at once see, must become a very serious consideration both to the Directors and the shareholders."

There was no difficulty in the construction of the bottom, which was evidently a mere chain of plates; in putting together the requisite sectional area it was necessary to adopt the cellular arrangement of the plates for practical convenience; for had all the plates been in one layer, this layer must have been 3 inches thick, and the uncertainty of the action of rivets through so many plates, more especially at the junction of the sides with the bottom, where the rivets must have been 8 inches long, rendered such a method of construction impossible. There was, moreover, an additional reason for cells in the Britannia Bridge, where, as we have seen, on account of the continuity of the tube, that portion of the bottom which is near the towers is thrown into a state of compression.

Many results were obtained, which gave some information for the construction of the top; for Mr. Hodgkinson had investigated the laws which govern the resistance of plates, bars, and cells to compression, and had made several experiments on transverse strain; and five experiments of a practical character had been made on a large model, under Mr. Stephenson's personal superintendence, at Mr. Fairbairn's works in London. The best method of uniting plates, the value of cells in resisting compression, the importance of pillars in stiffening the sides, the necessity for extra strength to resist the vertical pressure at the extremities, and of precautions against the slueing over of the tube, had all been there demonstrated, and many very important details of construction had been originated. These general facts, in conjunction with the investigations of Mr. Hodgkinson, furnished sound data on which to argue in designing a larger structure. The Author had, on the part of Mr. Stephenson, personally witnessed, or analysed, the whole of these experiments. He had been present at many of Mr. Hodgkinson's experiments in Manchester, and was the medium of communication between that gentleman and Mr. Stephenson, under whose instructions he had classified the results obtained, drawn such practical deductions as were immediately applicable to the structure in hand, and become acquainted with all the important principles on which it was determined to proceed. In order to obtain Mr. Fairbairn's practical assistance in elaborating the detail, the Author was directed by Mr. Stephenson to proceed to Manchester, and, in conjunction with that gentleman, to complete the drawings for the bottom and sides of the Conway Bridge.

The Author subsequently divided his time between Manchester and London, being in constant personal communication with Mr. Stephenson. He was assisted by Mr. Blair, by whom, under his immediate inspection and directions, the first drawings for the tubes were executed; and the general dimensions, thickness of the plates, and all important details involving any theoretical principles, were thus determined.

A design with considerable working detail was completed in July, in which the dimensions of the T-iron, angle-iron, and covering-strips, were all fixed. The top then consisted of two sets of rectangular cells, 2 feet 4 inches by 1 foot 9 inches, constructed principally of half-inch plates.

The manner in which the strength of this tube had been calculated will be understood from a communication to Professor Airy, who personally inspected the large model after it had been broken in the first experiment, and in his remarks to Mr. Stephenson kindly indicated the conclusions he had arrived at in thinking over the subject, and the simple method he had employed for calculating the strength of the real bridge from the result.

"Great George Street, Westminster,
"7th August, 1846.

"DEAR SIR,

"I am desired by Mr. Stephenson to forward you, as far as they are settled, the particulars of the tubes for the Conway Bridge, and to detail the manner in which the results are obtained, in conformity with your letter of July 20th.

"If the model be enlarged in every respect to $5\frac{1}{3}$ times its dimensions, as above, retaining the same thickness of plates, we should have another tube, with—

"Length, 400 feet; area of bottom, 49·4 inches; breaking-weight, 203 tons; depth, 24 feet; the length being now adapted to the Conway.

"The breaking-weight of different tubes will vary directly as their depth when their sectional area is constant, and will vary directly as their sectional area when their depth is constant; and, consequently, will vary as the product of these quantities when both are to undergo change.

" The sectional area of the top and sides being at present undefined, we have only to consider the sectional area of the base, which may evidently be substituted for the whole sectional area in the above position.

" Hence, 27 feet being the required depth, and 420 square inches the intended sectional area of the bottom of the tube for the Conway, we have,—

$$\text{Breaking-weight} = 203\,\frac{27 \times 420}{24 \times 49{\cdot}4} = 1940 \text{ tons.}$$

$$\text{And the weight it will support at centre} = 1940 - \frac{\text{wt. of tube}}{2} \text{ tons.}$$

The weight of the model can be no criterion for the weight of other tubes, on account of the unnecessarily great area of its top compartments. Could we ascertain the correct weight, it would doubtless vary in other tubes as the cube of the factor by which all their dimensions were multiplied.

" But, assuming the weight at even 1200 tons, it would then bear, in addition to its own weight, at the centre,

$$1940 - 600 = 1340 \text{ tons.}$$

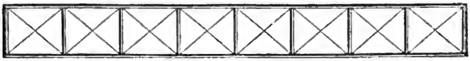
" Or 2680 tons distributed throughout, which, allowing a ton per foot for trains, is nearly seven times as much as can be required for practical purposes.

" EDWIN CLARK.

" To Professor Airy."

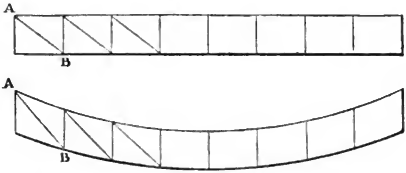
In reply to this communication Professor Airy kindly pointed out that the conclusion drawn in the last paragraph, as to the practical safety of such a bridge,—where it is stated that its breaking-weight is seven times as great as any weight with which in practice it can ever be loaded,—is not strictly correct; that the proper process would rather be, to find the whole actual strain, to multiply it by the factor of safety, and then compare the product with the actual strength. On such reasoning the bridge is already loaded from its own weight with one-third of its breaking-weight; and with an additional load of 400 tons, equally distributed, or 200 tons at the centre, would be loaded with nearly two-fifths of its breaking-weight, instead of one-seventh. But as the weight of the bridge is a permanent and invariable strain, whereas the load to which the bridge may be subjected in use is the only variable load which has to be considered, it appeared to Mr. Stephenson that when the weight of the structure formed so very important a part of the whole strain, he was justified either in making the assumption as above, and retaining the usual factor of safety, or otherwise in reducing the factor itself.

The determination of the proper thickness for the sides was a difficult problem. The strain is of a two-fold character, arising solely from the reaction of the weight of the tube at the ends. It may be conveniently understood by imagining the sides to consist of trellis-work as below.



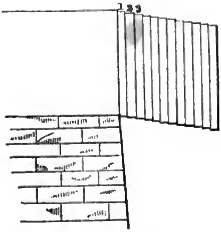
The compression in the top of the Conway Tube is at the centre above 2300 tons, and the tensile strain at the bottom is consequently of the same amount, and such a strain can only be induced from the vertical pressure at the ends by some diagonal action throughout the sides. If the thickness of the sides were considerable, this diagonal action would be partly a thrust and partly a tensile strain; but on account of the thinness of the sides, they would yield by buckling to any thrust, and it is probable that the diagonal strain is wholly tensile. Now, any tensile strain in a diagonal direction, tending to compress the top and extend the bottom, may be resolved into two parts, the one inducing the compression and extension, and consequently a horizontal strain; the other tending to draw the top and bottom together, and consequently a vertical strain. This vertical strain has to be resisted solely by the sides, which, on account of their thinness, are not stiff enough for this purpose, and consequently pillars become necessary to keep the top and bottom asunder. This was made evident by experiment at Millwall; and when the pillars were added, the diagonal tensions, as described, were also observed.

We shall form a good idea of the necessity of these pillars and their proportionate strength by conceiving the top and bottom of the tube to consist of inextensible and incompressible laminæ of metal, connected by vertical pillars, and very elastic square plates.



If such a system be now deflected, the pillars maintaining their length, the diagonals A, B, &c., will be all lengthened, and those diagonals will be most lengthened which are nearest the extremities, while the central plate will retain nearly its original square dimensions, and suffer but little distortion. The middle plate might, therefore, be removed without much affecting the action of the sides, while both plates and pillars require to be thicker as they approach the extremities, where their distortion is greatest. The pillars will, however, require strength at the centre from another circumstance, viz., that as the strain from the sum of all the extensions and compressions is there accumulated in the top and bottom, it is at this part of the structure that they will require the greater precaution to preserve them in form and prevent them from escaping out of the line of strain.

Another consideration in the sides had also to be attended to,—as to the strain called by Mr. Stephenson "the shearing strain," which rendered thick plates necessary at the extremities of the tubes. It is evident that the immediate strain from the weight of the structure, close to the piers on which it is supported, will tend to shear off the end of the tube in a vertical line, and that this strain will decrease as we approach the centre. It will also be principally resisted by the action of the sides. This will be understood by reference to the figure below. There 1, 2, 3, represent thin slices of the sides, the shearing strain at No. 1 being equal to half the weight of the tube: considerable section is evidently necessary to resist this tendency.



These considerations apply to a single independent tube; but with a continuous tube, as at the Britannia Bridge, the necessity of strong pillars and strong sides at the towers is still more evident. These pillars are actually constructed of two T-irons, face to face, covering the vertical joints in the side-plates. (See Plate XXII.) They occur every two feet throughout the tube, and serve at the same time for connecting the plates, which are ten-sixteenths thick at the extremities and eight-sixteenths at the centre.

Due regard was had to these circumstances in determining the thickness of the plates for the Conway Bridge, of which the details as regards the bottom and sides, were sufficiently matured in the month of August to warrant the ordering of the plates.

The dimensions of the cells were limited by those necessary to enable a man to pass through them for purposes of construction and subsequent repair. The lower plates in the bottom were double, to obtain sufficient sectional area. They were settled at twelve feet in length, as being the greatest size attainable without a great addition to their cost, while it was important to diminish as much as possible the number of joints. Great care was taken in the arrangement of the bottom to avoid weak places or sections by the occurrence of many joints in one line; the size of the rivets was settled at one inch, the number being regulated by the sectional area of the plates to be united. A circular inch rivet will be sheared by a strain of about 16 tons in the case of a single shear (fig. 1), but with a double shear (fig. 2) it will bear double that strain.

Fig. 1.

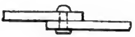
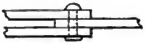
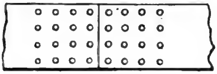


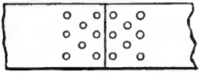
Fig. 2.



The riveting of the bottom was designed as described at p. 561, there being two layers of twelve-feet plates to connect together. It was considered at that time very important by Mr. Fairbairn that the rivets on plan should be arranged behind each other, or in lines in the direction of the length of the tube, for it was imagined that such an arrangement



interfered less with the strength of the plate than when the rivets occur as below. This assumption arose from consi-



dering a plate as a number of parallel fibres independent of each other, and, consequently, when one line of fibres is once destroyed by a rivet-hole it was conceived that other rivets in the same line would not further weaken the plate, whereas with the zig-zag riveting another intermediate line of fibres is destroyed, so that a plate riveted as above would be very weak, all its lines of fibres being separated. This conclusion, it will be shewn from future experiments, was proved to be entirely erroneous, the last riveting being the stronger; but the great value of friction from contraction of the hot rivets was then unknown.

The top had two sets of cells, and too much section, being to the bottom in the proportion of 4·2 to 3; but this part of the structure was still considered entirely *sub judice*, awaiting further evidence from Mr. Hodgkinson's investigations.

The oblong cells as originally proposed in the top were ultimately altered into square cells, and diminished in size as much as practicable, in accordance with the results of Mr. Hodgkinson's experiment on the crushing of cells. He advocated circular cells as still stronger than the square form, which were adopted for practical convenience in construction.

The drawings and lists of the large tubes for the Britannia Bridge were completed by the Author at Manchester on the 6th of November, Mr. Stephenson having been present at Manchester discussing the details.

The depth of the Conway Tube in the centre was settled at 27 feet, the ends being three feet less in depth. It is evident that the strength of the tube is in no way affected by either being cambered above the horizontal line, or bellied below it; and it was determined to build it with such a camber at the centre as would bring it ultimately as near to a straight line as possible.

As regards the outline for the Britannia Bridge, it was determined that the depth should be greatest over the centre tower, and should diminish towards the ends, the top forming a portion of a parabola, so that the decrease in depth became more rapid towards each end. The reasons for this outline were, first, the general appearance of the bridge, which would have been unsightly with a dip at the centre tower, and considered as a continuous tube, the greatest strain occurs over the centre tower, where the depth should, consequently, be the greatest. This form was evidently much more pleasing to the eye.

The Britannia and Conway Tubes may be considered as nearly similar tubes as regards their centre section, but the variation in the construction of the ends of the Britannia Tubes to meet the strain over the towers is very considerable. If the large model be considered as 1, then the lineal dimensions of Conway and of the Britannia large tubes will be $5\frac{1}{3}$ and 6 respectively, so that the Britannia is about $\frac{1}{7}$th larger in lineal dimensions than the Conway, except as regards width.

The most important modification which the design of the tubes underwent in consequence of the experiments, took place in February 1847, in accordance with the principles determined by Mr. Hodgkinson, in his inquiry on the crushing of plates, bars, and cells. The progress made in the manufacture of the plates rendered it essential to decide on the construction of the top, which had been arranged provisionally with two sets of cells, and in this form was undertaken by the contractors.

In models, where the plates were thin, as compared with the plates proposed to be used in the bridges, failure had taken place by the buckling of the top. When these same plates had been put into a corrugated form, or riveted in cells, as in the large model, this phenomenon had disappeared, and hence it was naturally concluded that a cellular structure was indispensable for the large tubes. So long as thin plates were employed this conclusion was perfectly correct; but the models with thick plates did not fail in this manner.

We have fully described Mr. Hodgkinson's interesting and complete investigation of this subject, of which the two most important generalisations, as regards our inquiry, were,—

That plates varying only in thickness resist buckling in the ratio of the cube of their thickness; and, moreover,

That the value of cells is dependent, first, on the proportion of the thickness of the plates to the size of the cells; and, secondly, on the form of the cell itself, round cells being stronger than square cells, and these being stronger than other forms experimented upon.

Thus with the great sectional area requisite, if plates of sufficient thickness could have been obtained for the purpose, there would have been no danger of buckling if only a single plate had been used for the top of the tube; but this plate would have been nearly 4 inches thick, which not being obtainable, it was necessary to fall back upon thinner plates. It was, therefore, now essential, first, to use the thickest plates it was possible to obtain, and, secondly, to put them together in some method convenient for practical construction, and at the same time in a good form for resisting any danger of buckling. The square form of cell, with three-quarter-inch plates, met these requirements.

The following were the reports made by the Author to Mr. Stephenson on this subject :—

"Canal Street, 25th February, 1847.

"Mr. Hodgkinson has obtained a very interesting result, by applying cast-iron patched on to the top of one of his wrought-iron tubes. It was a tube of uniform thickness, ½ inch everywhere; 2 feet deep, and 16 inches broad, and 30 feet between supports. He added *two* strips of cast-iron along the top, of 5 square inches sectional area *each*, and two similar strips of wrought-iron of 7½ inches sectional area each were riveted along the bottom. The sides were stiffened by a few vertical angle-iron pillars.

"The breaking-weight of this tube was originally 55 tons. With the above additions it bore 120 tons. It failed in both cases (as in almost all the experiments!), by the tearing asunder of the bottom. The cast-iron, of course, breaking when the tube fell.

"You will draw your own conclusions on the value of this result. He is very sanguine on cast-iron tops, and very anxious for further information on the subject. Will it be advisable to do anything further?

"He has two large tubes prepared for breaking, on the old plan. One he proposes to break by impact, to dispel the theoretical misgivings of mathematicians, and a few qualms of his own. The experiment is certainly conclusive as to the possibility of advantageously uniting cast with wrought-iron by means of rivets on a small scale. The cast-iron did its duty thoroughly well, and, had the tube failed originally at the top, we could have been certain that all the additional strength was due to the cast-iron; but I cannot help being struck with the fact, that all our large tubes fail by the tearing of the bottom. Has this anything to do with our *modus operandi* in the experiments? If not, I certainly see no grounds whatever for the great additional area of the proposed top of the Conway over the bottom. The first impression, from the small tubes, that a crushing of the top was to be feared, seems to have undue importance in the proposed bridges. At any rate, it is worth consideration, first, Whether the bottom of the bridges ought not to be increased in strength; and secondly, Whether one set of cells would not be sufficient at top, and especially, if the middle portion of the tube could be strengthened by cast-iron."

"Manchester, February 27, 1847.

"DEAR SIR,

"The settlement of the top is a difficult and unsatisfactory operation. With the sides, and bottom *as ordered*, and the double set of 18-inch cells at top as proposed, the Conway would stand thus:

Top sectional area	653	square inches.
Sides	259	„ „
Bottom	419	„ „

Now, the bottom area will have to be reduced by rivets; and, therefore, if the tensile and compressive strength of the metal is to be taken, as in the experiments, as nearly equal, we have an absurd inequality between the top and bottom. If the *thickness* of the top plates, which are here assumed at $\frac{1}{2}$ an inch, be reduced, the 18-inch cell becomes a weak cell, and ought also to be reduced in size, which is impracticable.

"In this dilemma, the following tube suggests itself: First, to increase the D plates, by adding another layer, so that they will then exactly resemble the E plates, viz. they will become 1 inch thick. This strengthens the bottom, which all experiments convince us is first to fail. It does not interfere with the plates ordered, and it insures the full benefit of the whole strength of the vertical plates.

"Secondly, the top may be made of only one set of cells $\frac{3}{4}$ inch thick, 18 inches square, with enlarged angle-iron, if required. We shall thus be using cells of such dimensions that we may calculate on the full resistance of the iron to *crushing*. The manufacture will be very much simplified; and the simplicity is a very strong recommendation for repairs, &c., and durability. The weight of the *whole* tube will be thus unaltered, and the calculated strength much increased. We shall stand thus:

Top sectional area	570	square inches.
Sides	259	„ „
Bottom	508	„ „

Total weight = 983 tons.

"I have suggested this to Fairbairn, and he at once acquiesces in it. He is very busy, and I do not see much of him. He assures me, that, far from there being any practical difficulty, it will be a very simple, and a very substantial affair.

"It is, at any rate, in the proportion that the only theoretical results we have acquired suggest, and has the advantage of being founded on experimental data. This top has fully occupied me at present, and the other matters are yet untouched. Its settlement is all-important.

"Mr. Hodgkinson is anxious for cast-iron. It will certainly do to patch the tube up with at any time, if it becomes weak in the back.

"The experiments are stopped until we hear from you; and it seems hardly worth while to go on any farther.

"E. Clark."

With respect to the employment of cast-iron in the top of the tube, we may observe that this material had been already so employed by Mr. Stephenson on a bridge at Chalk Farm, over the North-Western Railway. This was indeed the first application of hollow wrought-iron girders to the construction of bridges. This bridge is represented in Plate XLIII.

The top consists of an ordinary cast-iron flanged girder riveted to the sides, the ornamental cast-iron cap being merely for protection from the weather. The great depth was not adopted for strength, but as a screen from the road beneath. The details given in the Plate require no further explanation; they were kindly furnished by Mr. Dockray, the resident engineer of the North-Western line, with the following letter:—

"Euston Square, 2d July, 1849.

"My dear Sir,

"Mr. Stephenson directs me to send you the accompanying tracing of the box-girder bridge erected for the London and North-Western Railway, at Chalk Farm Lane. It is, I believe, the first of its kind.

"From my diary, I find that Mr. Stephenson gave me instructions to prepare the drawings on the 14th of July, 1846; on the 23d of the same month I find that Mr. Stephenson approved the drawing with some modifications; on the 25th September the work was let to Messrs. H. and M. D. Grisell, of the Regent's Canal Iron Works, City Road. In March 1847 it was completed.

"I am, my dear Sir,
"Yours very truly,
"Robert B. Dockray.

"*To Edwin Clark, Esq.*"

Mr. Stephenson determined on the use of the single set of cells for the top of the tubes without the introduction of cast-iron. He observes in a note to Mr. Fairbairn,—

"3d March, 1847, London.

"My letter to Mr. Clark would convey my concurrence in the proposed change in the arrangement of the top and bottom of the tube; and you would also observe, that I proposed to increase the dimensions of the top cells precisely as you suggested in your letter of yesterday. I attach some importance to the use of cast-iron, and in several bridges now in the course of construction, the top side of the tube is stiffened by this material; but this need not interfere with our present determination in reference to the Conway or Britannia."

This change in the construction of the top was, moreover, a great boon to the contractors for the tubes, as the difficulty of constructing two tiers of cells, even in short sections on their own premises, must have been very great; while the removal of such unwieldy masses, and the fixing of them together on the spot, must, from subsequent experience, have proved utterly impracticable; it is even difficult to conceive in what manner the single tier of cells on the bottom, composed of plates 12 feet in length, and so intricately combined, could have been ultimately united in such heavy portions.

This reduction in the top cells naturally reduced also the depth of the tube, and the sides being already ordered, it was impossible to remedy this unintentional change, and thus the present depth became fixed.

The lists of plates were now made out by the Author, and the first working drawings for the tubes may be said to have been completed; although in the progress of construction of the Conway Bridge many improvements were effected in the detail, while in the Britannia Bridge important modifications, both in principle and detail, were introduced, as further experience and more mature consideration of the subject suggested them. The estimated weight of the plates, exclusive of rivets, and the sectional area at the centre of both the bridges as then decided on, will be found in the following table:—

	Britannia Bridge.				Conway Bridge.	
	One large Tube, 472 feet long.		One small Tube, 274 feet long.		One Tube, 412 feet long.	
	Tons	Cwt.	Tons	Cwt.	Tons	Cwt.
Weight of the top	450	1	200	8	338	3
Weight of the sides	398	5	195	1	285	13
Weight of the bottom	436	19	201	17	314	7
Total weight	1285	5	597	6	938	3
Sectional Area at Centre:—	Square Inches.		Square Inches.		Square Inches.	
Top	640		499		608	
Sides	306		258		259	
Bottom..................	561		414		508	
Total..............	1507		1171		1375	

The estimated weight of the plates for the whole of the Britannia Bridge was, therefore,—

	Tons.	Tons.
Four large tubes, 1285·2 tons each	5140·8	
Four small tubes, 597·3 tons each	2389·2	
Two junction pieces, Britannia Tower, 100 tons each	200	
Total plates..............		7730

Conway Bridge :

	Tons.	Tons.
Two large Tubes, 938·6 tons each	1877·2	
Four additional pieces at the end, 18 tons each	72	
Total plates		1949·2
Total Plates for the two Bridges estimated		9670·2
Add Rivets 6 per cent on the weight		576·8
Total		10247·0

We have remarked that the tubes were constructed 6 feet longer at each end than the distance from face to face of the piers ; this was considered sufficient base for the tube to rest upon at each extremity, and any increase in this base would have involved deeper recesses in the towers. The width of the tube being 15 feet, there is thus a total base of 90 square feet on which the tube was to rest at either end, but the bottom of the tube being composed of thin plates, affords no strength as a beam transversely, and would bend if supported in the middle, and throw the weight almost entirely on the sides. This could not be remedied by the addition of transverse vertical plates in the cells, as it would have prevented all access for their examination ; nor was there sufficient height for the addition of such transverse plates of any depth within the tube itself, as the permanent way must then have been raised to pass over them. It was thus only possible to support the tube immediately beneath the sides, which were strengthened for that purpose. It was also necessary that the chains for the raising of the tube should be attached to the sides, without any assistance either from the top or bottom. To answer the double purpose, therefore, of securing a sound attachment for the lifting-chains, and of also strengthening the sides for the support of the tube's own weight, it became necessary to insert three cast-iron frames at each extremity of the tube, placed 2 feet apart, the outer pair of frames being intended for the attachment of the chains. The details of these frames will be explained in the description of the bridges. The chains are attached to these side-frames by means of transverse beams bearing against slots in the side-frames; and, lest the weight of the tube itself, when resting on the piers, should crush the vertical plates in the lower cells, it was proposed to bolt castings face to face on each side of these vertical plates; as shewn in Plate XIX. Some additional transverse strength was given to the bottom by means of the lower sill of the frames; and still further to provide against any great weight coming on the centre of the bottom, the bed-plates were placed only under each side, the centre being left hollow.

In order, also, to lessen the permanent weight on the bed-plates, and at the same time to secure the tube from any rocking motion on its base, Mr. Stephenson determined partially to suspend the tube in each tower, making special arrangements, as hereafter described, to allow for expansion.

To secure the tube in its raised position at the top of the recess, wall-boxes, as mentioned before, are constructed in the buttresses for the insertion of beams which permanently support the raised tube.

To ensure, moreover, a longer permanent bearing for the tube in the tower, it was proposed, that when raised on to these castings an additional length of six feet should be added at each end of the tube, thus increasing the permanent bed to twelve feet in length. Stiffening frames and castings in the cells were requisite in these additional pieces, to which, also, bolts for the suspension of the top were attached.

To assist in the arrangement of the great mass of cast-iron work thus necessary in the towers, a model to a very large scale, viz., half an inch to a foot of the whole of this apparatus was prepared by the Author, in Great George Street, under Mr. Stephenson's superintendence. The general principles of the frames and of the whole of the lifting apparatus and chains, together with the details of the bed-plates and rollers, and of the cast-iron work to build in the masonry, were thus determined. This model was subsequently sent to Manchester, and with Mr. Fairbairn's assistance, the working drawings for the cast-iron work were completed, and the model itself finished in detail.

In determining the requisite dimensions for the various beams, the strength was calculated from the usual empirical formulæ by Mr. Hodgkinson; and as the vertical ribs were in all cases unusually thick, on account of the small length of the beams, the errors liable to occur were all on the safe side. An unusual extension of depth was, however, requisite in the heavy beams for supporting the presses, and led to some apprehension as to their sufficiency. They were limited in the width of their flanges by the depth of the recess, and any increase in the thickness would have incurred serious risk from air-holes, and from the crystalline texture which large masses of cast-iron always assume in cooling. It was therefore proposed to use two beams placed on each other, in preference to a single beam of unusual thickness.

Wrought-iron beams were, however, ultimately substituted at the Britannia Bridge.

The cost of floating and raising the Conway Bridge was included in Mr. Evans's contract; but with respect to these important operations at the Britannia Bridge, Mr. Stephenson preferred that both the design and execution should be more immediately under his own direction. The necessary arrangements and the practical execution of his plans, in these operations, as well as the construction of the tubes, were consequently confided to the Author's sole management and control.

The supply of materials and labour, the construction of the iron pontoons, of the heavy forgings in the lifting-frames, and of the capstans, and other apparatus required, were contracted for by Mr. Charles Mare.

Few who peruse this brief summary of results will form any conception of the real difficulties overcome, and of the intense anxiety involved in their elaboration. It is easy to suggest; but under such weighty responsibility, experience adds only fresh difficulties to decision; and if the stranger who contemplates the finished reality that has been reared, requires so much thought to appreciate its principles and comprehend its detail, what weary hours must he have undergone who first conceived its bold proportions,—who, combating, almost alone, every prejudice that assailed him, and with untiring labour discussing every objection, listening to every opinion, and embodying every inquiry, has at length matured, step by step, the noble monument we are describing?

In carrying on such vast operations, involving an expenditure for several consecutive months of upwards of 6000*l.* a-week, it is evident that the engineer is greatly dependent not only on the diligence and care of his immediate assistants, but also on the intelligence and experience of the practical foremen who personally work out his instructions. He is indeed limited by their skill. Only twenty years ago the Britannia Bridge would have been designed in vain. Not only was there then no machinery or tools for the manufacture and working of such heavy plates, but that intelligent and valuable class of men who carry out such operations with an energy and skill in the practical detail, and a sound mechanical appreciation of what is required, which it is delightful to witness, was then not called into existence,—they are the peculiar offspring of railway enterprise, and among the most valuable fruits of its harvest.

The Author may be here permitted to bear testimony to their well-earned reputation, and to acknowledge gratefully the privilege he has enjoyed in being the medium of communication between so eminent a leader and a body of workmen in every respect worthy of being the instruments of his greatest achievement. With such elements of greatness fostered and appreciated by so enterprising a people, surely we may rejoice in the firm conviction that the prosperity and renown of a nation so endowed must still go on increasing.

The Author feels confident that he will be only anticipating Mr. Stephenson's wishes if he individually enumerates the services of some on whom he has been more immediately dependent.

To his brother, who has been his constant colleague, he feels most deeply indebted. The execution of every detail has been under his immediate charge, and Mr. Stephenson has been pleased to bear the most flattering testimony to the zeal and industry with which his trust has been executed, and the watchful economy with which the detail of such vast expenditure has been controlled.

To Mr. M'Laren, who both at Conway and at the Straits has superintended the construction of the tubes and the fitting of the cast-iron work and raising machinery, and whose practical arrangements and valuable suggestions have been of most important service.

To Mr. Muirhead, by whom the arrangements for floating and the whole of the timber-work have been superintended with exemplary industry and skill.

To these individually, and to their intelligent assistants, the Author would express his great obligations for the willingness and unabating perseverance with which they have invariably seconded his wishes and assisted him with their cordial co-operation through many difficulties. They have thus been the principal instruments in procuring for him that tribute of approbation which, while it belongs to all, it has been his more immediate province to receive.

It is, indeed, a source of high gratification to have been instrumental in realising so magnificent a conception of a master mind; and it is a pardonable vanity to believe that such a record of the industry of an intelligent people will increase in interest when all traces of this once busy scene shall be effaced; when the noise of the hammer has ceased, and the ephemeral village of the builders has disappeared; when the fern and the moss shall have ventured to invade even the massive pile that has displaced them; when the sea-weed with its coral inhabitants shall have mantled the foundations, and the wild bird, so long affrighted, shall return to its solitude, and rear its progeny beneath the marble shelter of the towers.

SECTION VI.

DETAILS OF CONSTRUCTION OF THE BRIDGES.

CHAPTER I.

THE MASONRY AND SCAFFOLDING.

We have in the last Section continued the history of the various modifications these singular structures have undergone from their first conception by Mr. Stephenson down to the period at which the designs were so far matured as to enable him to complete working drawings in sufficient detail for the commencement of the work.

Without stopping to recount how further changes have originated, we shall now describe the ultimate construction in detail. In describing the masonry we shall keep each bridge distinct, though such a separation will be departed from in treating of the tubes.

THE CONWAY BRIDGE.

The towers of this bridge, as originally designed by the architect, Mr. Francis Thompson, were intended for the application of chains, their height is, therefore, greater than would otherwise have been necessary, and the general effect is on this account, as well as from the omission of the stepped winged walls, much interfered with.

The accompanying Plate represents the original design.

The style of architecture which has been adopted is in accordance with that of the neighbouring Castle and Suspension-Bridge.

The lofty towers of the Castle overhang the western approach to the Bridge, and the line passes into Conway through an opening pierced in the embattled wall, which entirely surrounds the town. These fortifications are in good preservation, and rank among the most perfect examples of the strongholds of the thirteenth century.

In the original design the tube was proposed with a casing, having a machicolated cornice, stringcourses, and loopholes along its entire length; by means of this accessory, the tube was aptly connected with the towers, and harmonised with their character, but on account of the weight, and the great expense of executing the casing in any durable material, this intention was abandoned.

Foundations for both towers were obtained by stepping, and levelling the rock, at nearly low-water mark, excepting at the south-east angle of the Conway Tower, where, on account of the shelving of the rock into deep water, piles were driven into the silt, and a platform 2 feet below low-water formed thereon to receive the masonry. (See Plate XXXVIII.) The piles and platform together contain about 4800 feet of Memel timber. The masonry is faced throughout with mountain limestone, from quarries in Anglesey and the Great Orme's Head; the courses vary from 1 foot 6 inches to 3 feet in thickness, the stones weighing from 5 to 8 tons, the whole quantity of limestone being 161,450 cubic feet.

The external surface, up to the level of the underside of the tubes forming the base of the towers, is quarry faced with boasted or smooth angles, excepting the dressed recesses or grooves in which the tubes were raised.*

The whole of the exterior work above the base is built of dressed ashlar, the backing throughout is of Runcorn stone and some brickwork, the latter used more especially in the upper parts of the towers: all the beds and joints are dressed fair, and the whole of the masonry is set in mortar made with Aberthaw mountain limestone. The whole quantity of Runcorn stone is 191,255 cubic feet.

The backing of the walls is built with a description of fire-brick from Buckley mountain, set in the best Roman cement, with an equal proportion of sand. Some experiments on the crushing weight of these materials have been given.

For the purpose of floating the tubes into the recesses or grooves, the upper portion of the centre and south piers, forming the sides of the recesses in each tower, were temporarily supported by corbelling out the masonry at the lower part of the towers; and upon the admission, and previous to the raising of the tube, the lower portions of these piers were built up, and a direct bearing upon the foundations obtained.

It will be observed in Plate XXXVIII. that the overhanging watch-towers had also to be supported upon this corbelling, to allow of the completion of the upper part of the masonry previous to the floating of the tubes. To assist in supporting the great weight of the angles, which overhung nearly eleven feet, cast-iron brackets were tailed into the masonry and counterpoised by the superstructure.

Cast-iron beams were also inserted across the interior of the tower for carrying the permanent way. These beams, with the brickwork for that purpose, are shewn in the section at Plate XXXIX.; and a grating in the timber-floor on this brickwork allows free ventilation through the cells in the bottom of the tubes.

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* These bases were intended, in the original design, to have a boasted or smooth face, in order that all the intersections with the splayed surface might form true and perfect lines, and also to preserve a more connected appearance in the general mass, but from motives of economy a quarry face was substituted.

Castings precisely similar to those described in the Britannia Tower, as shewn in Plate XXIII. and marked F, were tailed into the masonry of the recesses, a little below the level of the top of the tubes, for carrying the channel-beams and balls, by which the tube is suspended. Large castings were similarly inserted longitudinally, to support the beams on which the press immediately rests. These castings may be considered as brackets; they are 15 feet long, their object being to prevent the flushing of the angle of the masonry on which the press would otherwise rest; they are marked A 3 in the above Plate.

The beams for carrying the press marked A 1 were not removed with the presses, as their value scarcely equals the cost of removal, and they are employed for carrying the masonry of the tower, which was subsequently built in, above the tubes. The space between the top of the tube and this masonry is filled up by light cast-iron plates. The cast-iron beams used for the guide-rods, in conjunction with the presses, were secured only in a temporary manner in the masonry of the upper part of the tower, and have since been removed. The whole quantity of cast-iron thus permanently built into the towers amounts to 325 tons.

For the better preservation of the structure, slated roofs have been constructed in the towers; and in order to conceal the undressed masonry and skeleton appearance of these roofs, the interior of the towers is arched, and the walls lined with brickwork, rendered in cement.

This masonry has been executed in a highly satisfactory manner by Mr. W. Evans the contractor, and was superintended by Mr. Bennett, under the direction of Alexander M. Ross, Esq., C.E. The contract for the masonry was let on the 6th of May, 1846; the first stone was laid in the north-east angle of the Conway Tower on the 12th; it was sufficiently advanced for the floating and raising of the first tube in March 1848, and entirely completed in February 1849.

The scaffolding used by Mr. Evans was of the usual character employed in modern buildings, the stones being hoisted by travelling cranes. Many of these details will be better illustrated by reference to Plates XXXV., XXXVI., and XXXVII., in which the artist has not, in any instance, sacrificed accuracy for picturesque effect. The sketches for the drawings were made with the camera, and the details may, therefore, be depended on as being in perfect proportion. The total cost of the masonry was 38,500*l.*

THE BRITANNIA BRIDGE.

Considerable difficulty was experienced by the architect in adapting any one style of architecture to the very peculiar requirements of this structure. The principal object in the design for the towers and approaches to the bridge was, the adoption of such a character as would best accord with the tubes, the external appearance of which is simply a representation of beams of gigantic proportions.

With this view, a combination of the Egyptian and Grecian styles appeared to be the most appropriate for the purpose,—the former as applied to the general and more massive portions of the design, and the latter to the less ponderous parts and to the details generally.

In order to render the design effective and appropriate to a work of such surpassing novelty, the proportion and finish of all the various masses and details were long and studiously considered, and only such accessories have been introduced as tend to express design, and impart a suitable character to the work.

The reliefs introduced at the level of the tubes may not inaptly be conceived to represent the connexion of the tubes with the masonry at these places, by means of massive frames and bolts; these reliefs are strongly defined by deep recesses and bold projections.

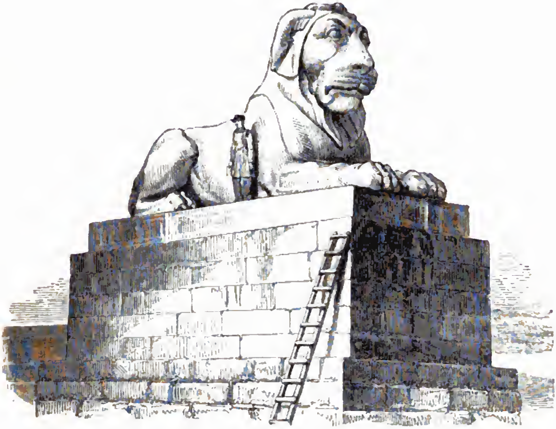
The three central towers are open at the top, after the manner of campaniles. This mode of termination, boldly contrasting with the solid and massive character of the substructure, imparts a more finished and pleasing appearance to the towers than could have been obtained by the adoption of solid tops.

The abutment towers terminate with an entablature, surmounted by a pedestal; and at each entrance into the tube the following inscription is deeply engraved upon the frieze of the entablature:

ERECTED ANNO DOMINI MDCCCL
ROBERT STEPHENSON ENGINEER

The wing walls are finished at the top with a bold cornice; and the stringcourse at the level of the bottom of the tube is continued up to the pier which terminates the masonry of the approaches. This stringcourse, together with the one at the level of the top of the tubes, exists on all the towers, and is made to range with the margins on the top and bottom of the tubes. It greatly assists, in appearance, the union of the several tubes with the towers, and further serves to connect them into one continuous beam, from abutment to abutment.

At the entrance of the approaches to the bridge, colossal lions of antique form, couchant on lofty pedestals, terminate the wing walls of the approaches, and form noble and striking objects in harmony with the structure, and may be considered as allegorical representations of the strength of the edifice and boldness of the undertaking.



The general surface of the masonry is left with a rough or quarry face; and considerable effect is obtained by contrast with the smooth-dressed portions of the work. The angles of the structure throughout the quarry-faced masonry are dressed smooth, so as to form narrow margins; and by this means the outlines of all the masses are defined with precision. The external masonry is faced with mountain-limestone or Anglesey marble, from quarries in the Island of Anglesey, opened by the contractors Messrs. Nowell, Hemingway, and Pearson.

The internal work is of Runcorn sandstone, with some brickwork, the latter being principally used in the abutments and in the upper parts of the towers.

The exterior masonry of the recesses or grooves, the string-courses and reliefs at the level of the tubes, the upper parts of all the towers, the crowning members of the wing walls of the approaches, the lions with their pedestals, and the angles in the quarry-faced work throughout the structure, are dressed fair.

All the beds and joints of the masonry are dressed fair, and the whole of the work is set in mortar made with the broken fragments of the limestone: the bricks, which were manufactured by the contractors, are set in Roman cement.

The Britannia Tower.

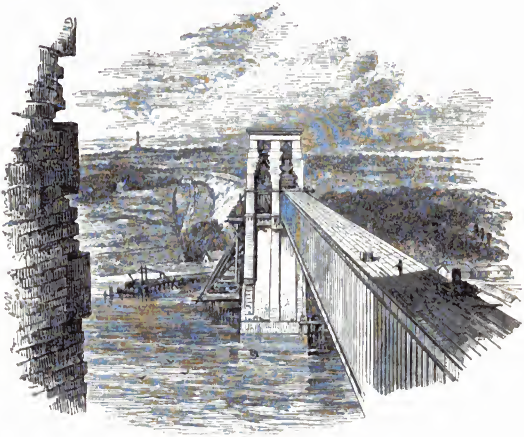
The centre tower is 221 feet 3 inches high, with a batter of 1 in 36 on all sides. The base is 60 feet by 50 feet 5 inches. The foundation-stones are placed on a stepped bed blasted in the rock, which consists of chlorite schist. The courses vary from 3 feet 3 inches to 1 foot 8 inches deep: none of the courses beneath the tube are less than 2 feet. The general form of the rock will be seen in Plate V. The plinth is at a height of 25 feet 6 inches above the foundations, which are exposed at low-water. The plinth is 3 feet out of water at highest tides. The tower is not solid; two rectangular wells extend from the basement to the level of the tubes, as shewn in plan at A B, Plate VIII. The external walls parallel with the tubes are 10 feet 6 inches in thickness, but the batter reduces them to 8 feet at the level of the bottom of the tubes. The internal wall is 8 feet 4 inches thick throughout, and the walls at right-angles with the tubes, forming the backs of the recesses are 6 feet in thickness from top to bottom. The lower part of these wells is filled with rubble masonry in mortar to the height of the plinth. The depth of the recesses at the base of the tower is 8 feet 6 inches by 15 feet 4 inches broad. The batter reduces the depth of these recesses to 6 feet at the level of the tubes. At the level of the bottom of the tube the piers forming the sides of these recesses are intercepted by wall-boxes of cast-iron, which are built into the masonry immediately beneath the stringcourse, for the insertion of the permanent cast-iron beams, for supporting the tubes when raised to their permanent height. Beneath the wall-boxes, as shewn in Plate IX., cast-iron beams, 15 feet long, are set in the masonry, to prevent the flushing of the angle of support.

The shelf that supports the castings from which the tube is permanently suspended is strengthened by similar smaller castings built in the walls. The wrought-iron beams used for supporting the presses were not retained as a permanent portion of the structure, as at Conway; but one of the cast-iron beams, originally intended to be inserted through the wall-boxes, was substituted for that purpose; and on this beam the masonry was carried up for filling-in the gap occupied by the presses as soon as they were removed.

The cast-iron beam used for the guide-rods is retained as an important permanent tie in the masonry. The *antæ* of the campanile top are supported on corbelled brickwork in the internal angles of the towers. The sections and elevations in Plates V., VIII., and IX., will fully illustrate these details: the recesses in the side-walls, shewn in plan C D in Plate VIII., were for the purpose of facilitating the junction of the tubes in the towers.

This magnificent tower contains 151,158 cubic feet of Anglesey limestone, 127,001 cubic feet of Runcorn sandstone, and 68,411 cubic feet of brickwork, in all weighing 24,700 tons. Including the bed-plates it contains also 479 tons of cast-iron, and the weight from the two tubes will be about 4000 tons. The total weight at the foundations is thus 29,600 tons, or 16 tons per superficial foot of sectional area; whereas the weight required to crush the lower courses would be about 500 tons per superficial foot.*

The nature of the vast and effective scaffolding erected by the contractors for the construction of this tower will be seen in Plate IV., which represents the Carnarvon Tower in course of construction, where the scaffolding was on a similar principle. The timbers are all whole balks, from 12 to 16 inches square, and from 40 to 60 feet in length, connected by bolts



	Tons.
* Stone-work, &c.	24,679
Cast-iron	479
Two tubes, say	4,000
Junction and castings	380
	29,538

Area of tower at base, 1847 square feet.

with butt-bearings. The whole height was nearly 250 feet; and at this vast elevation stones of eight or ten tons weight were transported over all parts of the tower with perfect ease. Notwithstanding the constant heavy winds to which this lofty scaffold has been exposed, it has stood without injury. A steam-engine erected on the Britannia Rock at the base of the tower was employed for raising the stones, with travelling gantries for laying them over all portions of the work. A view of the approach to the bridge, and of the Island of Anglesey, from the Britannia Tower, is represented on the opposite page.

The Side and Abutment Towers.

The principal difference between the side-towers and the centre tower arises from the absence of recesses on the land-faces of the former, the tubes for the land-spans being built in their places, and not raised from below. The foundations are all on solid rock; the rocks on either side of the Straits and at the centre being distinct in character; the Carnarvon Tower is based on a dark, shaly clay, belonging to the old red sandstone formation: the Britannia and Anglesey Towers are both based on a micaceous schistose rock, or chlorite schist: the Carnarvon abutment dips into strata of carboniferous limestone.

The masonry is of the same description generally as in the centre tower; but the height of the side-towers is 18 feet less than the Britannia, being only 177 feet 6 inches above the plinth. The height of the abutments is 35 feet less than that of the side-towers. The dimensions of the side-towers at the base are 62 feet by 39 feet; or above the plinth, 60 feet by 37 feet. These dimensions are reduced by the batter of the towers to 59 feet 6 inches by 36 feet 6 inches, at the level of the tubes. The extreme height to the tops of the campaniles is 53 feet above the top of the tubes, the greater portion of which height was requisite for the presses.

The lintels over the openings through which the tubes enter the towers on the land-side consist of single stones, 20 feet long, 2 feet 2 inches deep, and 2 or 3 feet wide. The masonry above these lintels is corbelled over with large stones, forming a concealed arch, in such a manner that the weight of the superincumbent work is not supported by them.

The whole weight of cast-iron in each of the side-towers is 382 tons, and is similar in every respect to the cast-iron work in the Britannia Tower before described, except that the wall-boxes occur only on the inner face, as shewn in Plate X. Each tower contains about 120,000 cubic feet of limestone, 100,000 cubic feet of sandstone, and 35,000 cubic feet of brickwork. The whole weight of the tower is about 18,000 tons, which, together with 2500 tons, the weight of the two tubes, gives a pressure of 13 tons per superficial foot on the lower courses of the masonry.

The Abutments.

The two abutments are uniform in their plan; but on account of the bold rise on the Carnarvon side of the Straits, the height of the masonry to the top of the abutment is only 88 feet, while the Anglesey abutment is 143 feet. The embankment on the Carnarvon side is continued close up to the abutment tower, no arches or viaduct being necessary, while the great height of the Anglesey abutment rendered it advisable to stop the embankment at the entrance of the masonry, and carry the line through the abutment upon brick arches, supported on brick piers from the rock below. Full details of this somewhat intricate mass of masonry and brickwork will be found in Plate XII.

The walls at the face of the abutment towers are 10 feet

6 inches thick, and they are reduced at the level of the tube to the same dimensions as the corresponding walls in the side-towers. The embankment, which is 80 feet high, is sloped off in the interior of the abutment, and also externally.

A lofty longitudinal arcade wall of 22 feet spans is built in the centre of the abutment, from which spring waggon-headed arches to the external walls, and upon these a series of small brick arches is constructed transversely, for the support of the permanent way.

A somewhat similar system of arches, resting partly on the ballast of the embankment, carries the permanent way between the pedestals of the approach; while the open area in the abutment-tower is covered by brick arches upon cast-iron beams. Over the entrances to the tubes are massive lintels, consisting of single stones, 20 feet long, and the approaches are marked by colossal lions couchant on pedestals. Their length is 25 feet, and weight of each about 30 tons. They are each composed of 11 pieces of limestone, and are 12 feet in height; they were designed and executed by Mr. Thomas, who has been extensively engaged on the sculpture of the new Houses of Parliament. Some idea of the perfection of the scaffolding may be formed from the fact that one of these lions was brought from a workshop at the base of the abutment, raised 110 feet, and put together complete on the pedestal, in one single day.

The marble, or carboniferous limestone, of which these lions and a great part of the masonry are constructed, is quarried at Penmon, at the northern extremity of the Island of Anglesey, where it occurs in great abundance and in regular strata of convenient thickness; it abounds in madrepore and other fossils, and is capable of receiving a very high polish, and some of the specimens manufactured into ornaments are exceedingly beautiful. These quarries, extending several miles along the coast, were opened, and worked by the contractor.

A colossal figure of Britannia was designed by Mr. Thomas for the centre tower of the bridge, but its great cost prevented its construction; it is represented on the cover of these volumes.

The whole quantity of material in these towers and abutments, together with their respective heights, will be found in the following tables :

Masonry of the Britannia Bridge.

	Carnarvon Abutment.		Carnarvon Tower.		Britannia Tower.		Anglesey Tower.		Anglesey Abutment.		Total.	
	Cubic Feet.	Weight in Tons.	Cubic Feet.	Weight in Tons.	Cubic Feet.	Weight in Tons.	Cubic Feet.	Weight in Tons.	Cubic Feet.	Weight in Tons.	Cubic Feet.	Weight in Tons.
Limestone	80,792	6,733	98,737	8,228	151,158	12,596	118,274	9,856	145,906	12,159	594,867	49,572
Do. in Lions	3,569	297							3,569	297	7,138	594
Runcorn Sandstone	59,896	3,993	99,414	6,627	127,001	8,466	107,346	7,156	148,998	9,934	542,655	36,176
Brickwork	30,931	1,546	32,556	1,628	56,558	2,827	30,850	1,543	126,982	6,349	277,877	13,893
Rubble	12,837	856	2,106	140	11,853	790	7,641	509	35,177	2,345	69,614	4,640
Summary	188,025	13,425	232,813	16,623	346,570	24,679	264,111	19,064	460,632	31,084	1,492,151	104,875

Vessels with Limestone discharged	1,210
Ditto with Runcorn discharged	531
Ditto with Coal, Sand, Cement, &c.	436
	2,177

Height of Towers.

	Britannia Tower.		Carnarvon Tower.		Anglesey Tower.	
	Ft.	In.	Ft.	In.	Ft.	In.
Below plinth	25	6	11	11	26	7
To bottom of tube	97	0	97	0	97	0
Depth of tube	30	0	27	2	27	2
Quarry face	41	0	28	4	28	4
Dressed face	8	0	6	0	6	0
Pilasters	9	0	9	0	9	0
Architraves	6	0	6	0	6	0
Cornice	4	9	4	0	4	0
Total	221	3	189	5	204	1

Height of Abutments.

	Carnarvon.		Anglesey.	
	Ft.	In.	Ft.	In.
Foundation to bottom of tube	42	7	98	4
Depth of tube	23	0	23	0
Frieze	5	0	5	0
Cornice	5	0	5	0
Dado	10	0	10	0
Coping	2	0	2	0
Total	87	7	143	4

This enormous mass of material has been brought partly from the Island of Anglesey, about 16 miles distant, and partly from Runcorn, in Cheshire, and the iron mostly from Staffordshire. The average height to which it has been raised is 80 feet, and the stonework has occupied 2 years and 9 months in its erection. During all this time the masonry has been set at the rate of 3 cubic feet per minute.

When the tedious nature of much of the workmanship is considered—when the punching of the holes and the insertion of the rivets—the quarrying, carrying, and working of the stone—the construction of the intricate machinery for floating and raising, and the actual manufacture of so vast an amount of iron—is taken into account, this work will probably prove one of the most extraordinary monuments of human industry which any country can boast.

Three steam-engines were employed for raising the stones of the towers and abutments, with 26 travelling-cranes over different parts of the work, simultaneously engaged in transporting and setting them; 2177 cargoes of stone and other materials were discharged for the masonry alone. The stones were worked on the shore on either side of the Straits. From 500 to 600 men were constantly employed in the erection of the towers, besides 300 or 400 men occupied in the quarries, and in bringing the stone to the Straits. The supply was sometimes delayed by contrary winds, and a few vessels were wrecked, but none lost.

The magnificent scaffolding for the land portions of the tubes between the abutments and side-towers is faithfully represented in Plate II. On the Anglesey shore this platform is of colossal dimensions, its height being 100 feet. As a piece of construction it is admirable, and the regularity of the bays and cross-struts gives it a most picturesque appearance. The whole weight of iron-work supported on this scaffold was about 1200 tons, or 9 tons per foot run. It consists of 13 bays, or rows of upright timbers, placed 18 feet asunder, each bay contains 6 uprights, which are about 15 inches square, and 12 feet apart; but the weight of the tubes is supported exclusively by the 4 centre ones, which sustain, in consequence, an average weight of 20 tons each. In some instances, a weight of 175 tons has been sustained upon four supports only. The horizontal timbers were somewhat compressed under this strain, but the stability was in no way endangered, the uprights being much assisted by the diagonal struts. The platform on the top is 78 feet broad, and is rendered most conveniently accessible by means of a broad flight of steps within the scaffolding. The workmen are sheltered from the wind by a close palisade on either side. This immense platform presents an area of 18,000 square feet at this elevation, and contains 76,363 cubic feet of timber. The scaffolding for the Carnarvon small tubes is similar in every particular, but is not so lofty; it has an average height of about 60 feet, and contains 42,000 feet of timber.

The whole quantity of timber employed in the scaffoldings for the masonry was 175,000 cubic feet, and for the construction of the land-tubes 118,230 feet. The platforms on which the large tubes were constructed contained also 110,105 cubic feet; the total quantity of timber employed as scaffolding for the whole bridge being thus 403,335 feet. It was contracted for by Messrs. Nowell, Hemingway, and Pearson, and principally constructed by their able and confidential assistant, Mr. James Greaves.

Great precautions were taken to preserve the scaffolding from fire, to which the number of red-hot rivets constantly thrown about continually exposed the scaffolding for the land-tubes, which on several occasions actually took fire. The means at command for extinguishing it were, however, so complete, that it was on all occasions immediately and easily subdued, or the consequences would have been most serious, as the tubes themselves would inevitably have been destroyed, having no other support during their construction. To avoid such a disaster, two fire-engines were constantly on the spot in working order; and tanks containing eight thousand gallons of water were erected on the scaffolding at either abutment, with cast-iron pipes leading to all parts of the scaffolding. Gangways were also constructed beneath the flooring, and pliable hose, ready for attachment at any portion of the structure, afforded ready means of deluging any part of the platforms with water. The water was pumped into the tanks from cisterns, which were supplied from land-springs in the neighbourhood, constantly flowing into them in wooden channels for that purpose.

A railway was laid on the top of the platform, to carry the travelling-cranes for the construction of the tubes, which are built at a distance of 9 feet asunder. The plates were raised from below in large sections, weighing 6 or 8 tons, by means of crabs, worked by hand. This immense accumulation of masonry and scaffolding was erected under the experienced superintendence of Frank Forster, Esq., resident engineer, the masonry being intrusted to the immediate supervision of Mr. T. E. Rawlinson, the resident clerk of the works; the scaffolding for the tubes was under the charge of Mr. Matthew Forster.

CHAPTER II.

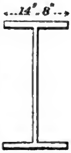
DESCRIPTION OF THE TUBES.

In describing the tubes it will be unnecessary to give distinct accounts of each bridge, for if we consider one of the large spans of the Britannia Bridge as an individual beam, we shall find it almost identical in principle and detail with the tubes used at Conway.

The most important variation arises from the circumstance, that the Britannia Tube was constructed with a twofold object: First, it had to sustain itself as a simple and independent beam, for the purpose of floating it, and raising it to its place; and, secondly, it had to be combined, when in its place, with the other portions of the bridge, and then to become part of a continuous beam 1511 feet long, supported at each extremity, and at three intermediate points in its length. In proportioning the thickness of the plates, this two-fold object was kept in view; the large tube is thus not designed as it would have been had it been intended either merely as a portion of a continuous tube, or as a tube wholly independent of continuity.

It will facilitate our explanation of the peculiarities of a tubular beam, if we do away with the consideration of the cells, the rivets, the covering plates, and the pillars in the sides, and consider the beam as constructed of a single mass of iron, forged or welded into the required shape, without any joints or rivets.

For this purpose, we must imagine all the material contained in the cells at the top, which is effective in resisting the horizontal strain to be collected in the top into a single plate, or top flange. We shall similarly bring the plates in the two sides into juxtaposition, and condense the effective material in the bottom. We shall then form a flanged girder of wrought-iron, as in the sketch; and preserving the width of 14 feet 8 inches throughout, the following table will shew the thickness of each element of the beam at every part of its length:—

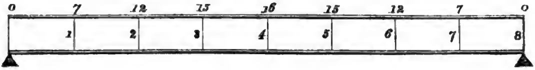


Distance from the Extremities.	Thickness of the top Flange.	Depth and Thickness of the Vertical Rib.	Thickness of the bottom Flange.
Feet.	Inches.	Ft. In. Inches.	Inches.
0	3	18 5 × 1·25	2·1
50	3·13	19 4 × 1·12	2·2
100	3·38	20 1 × 1·00	2·5
150	3·64	20 10 × 1·00	2·99
centre.	3·83	21 5 × 1·00	2·99

This will be a representation of one of the tubes of the Conway Bridge, excepting as regards weight, for all the covers and rivets added to this elementary tube, although requisite for its construction, add nothing to its strength, but increase its weight by about 31 per cent.

We have made no allowance for the weakening of the plates, in consequence of the holes punched through them; and although this in the top is unimportant, yet in the bottom the sectional area must certainly be to some extent diminished, though not to such a degree as might at first sight be imagined.

It will be observed, that the top flange is thicker in the centre of the span than elsewhere, though not in the proportion which the theory of beams would indicate, for, as we have seen before, the strain at every part of a beam is proportionate to the product of the distances of that part from either extremity; so that if we suppose our beam, as in the sketch below, divided into eight equal portions, and if the strain at the centre be represented by 4 × 4, or 16, the strain at 3 will be 5 × 3, or 15; at 2, 6 × 2, or 12; at 1, 7 × 1, or 7; and at the end, 0; since the thickness of our top flange is 3·83 at the centre, to determine the thickness at No. 2, we should have as 16 : 12 :: 3·83 : 2·87; whereas, the thickness is 3·13; moreover, the thickness of the top at the ends would be 0, whereas we find it to be 3·00. It would evidently be absurd to form a beam without any top or bottom at the extremities; indeed, this theory of strain relates only to *horizontal* strain, whereas the more important office of the top at the extremity of the tube is to preserve the sides in form and to assist them in supporting the vertical weight of the tube itself; although the horizontal strain thus disappears at the extremities, the vertical shearing strain caused by the weight of the tube actually increases, and hence the necessity for the increased strength of the vertical web at each extremity: the subject is involved in some difficulty, but it is highly probable that the vertical rib at the centre might be reduced to nothing, where the thickness of the top and bottom flanges is at a maximum. To meet these views to some extent, the thickness has been varied as in the table.



Mr. Hodgkinson had made a most valuable series of experiments on models varying in thickness in the above ratio; and considering the sides, which were of considerable substance, as an element of resistance to the horizontal strain, he had varied the thickness of the sides in the same ratio as that of the top and bottom; the ends of some of his models, in consequence, failed by destruction of the sides so tapered off.

In the designs for the bridges, the sides have been considered by Mr. Stephenson as no important element of strength as regards horizontal strain, but have been regarded as the connexion of the top and bottom portions of the structure, to preserve them in shape and resist the shearing of the extremities. Now the weight of the beam is 1112 tons, consequently, when resting on the piers, it exercises a direct pressure of 556 tons on each pier. We find, moreover, in our table, that the sectional area of our vertical rib, close to the pier, is 276 inches, or 18 feet 5 inches deep, and 1¼ inches thick; the shearing force per square inch, therefore, tending to slice off this end of the tube, is 2 tons, the ultimate shearing resistance of such iron being about 20 tons; but as the plates are wholly connected by rivets, it is evidently necessary that there should also be sufficient rivets to resist this shearing force of 556 tons. Now the number of rivets in this vertical section will be found to be 148, making a total area to be sheared of 227 inches. There is thus a strain of 2·4 tons per inch tending to shear all the rivets. In this way, the number of rivets necessary, and the quantity of material that is indispensable in the sides, is indicated.

Leaving the ends, and going to the centre, of the tube, and taking the depth of the centre of the cells, we have a force of 2346 tons compressing the top flange, and the area of the top flange being 645 inches, this strain gives 3·63 tons per square inch of compression; whereas, independent of flexure, such iron should resist ultimately 15 tons per inch; this gives the quantity of material requisite at the centre, and indicates the best method of uniting it, viz., by butting the plates in close contact with each other, and making every possible provision against the escape of these plates from the line of pressure, which is done partly by the sides, and partly by means of covers riveted over the joints, and by angle-irons connecting the corners. Permanence of form is further secured by the cells, and gussets, and transverse beams inside.

In the bottom flange similarly we have 535 square inches at the centre, or 4·35 tons per inch of tension. Thus the quantity of metal there required is determined. Since the tensile strain in the bottom, unlike the top, is transmitted entirely through the rivets, it is necessary there should be not only sufficient sectional area of plates, but also of rivets, to be sheared to resist this prodigious tension, tending to tear the bottom asunder. The number of rivets at any section of the bottom is in this manner proportioned. The plates are united by covers of sufficient size to allow of the requisite number of rivets. The angle-irons are rendered continuous by short covers over every joint; and the whole is put together in the form of rectangular cells for convenience of workmanship, with transverse stiffening plates to resist distortion and carry the permanent way.

The sides throughout, on account of their great height, are carefully protected from flexure by pillars of T-iron face to face every two feet, by vertical plates united with angle-iron near the ends where the T-iron was thought insufficient; and over the towers by means of cast-iron columns riveted to the wrought-iron work. They are, moreover, strengthened throughout by corner-pieces, or gussets, connecting them with the top and bottom; and the plates are carefully united by covers over every joint.

If we now make a skeleton girder of the Britannia Bridge, we shall find a different distribution of the metal in the top and bottom flanges, more particularly at the extremities, which are ultimately united in the towers. To form a continuous beam, we shall find more precautions have been necessary to stiffen the sides, on account of their increased depth, and of the severe strain entailed upon them at their bearings on the towers. We shall find the construction of the top, moreover, modified to meet the tension to which it will be subjected over the towers.

We have seen that, horizontally, the strain in the top of the independent tube was 0 at the ends; but when the extremity becomes united with the neighbouring tube, the strain becomes greater than even at the centre of the spans. The covers, therefore, in the top are no longer simple strips, with a single row of rivets for the mere purpose of keeping the plates in shape, but they become long covers, with numerous rivets of sufficient section to meet this tensile strain; and every joint in the angle-iron is also protected by requisite covers, as in the construction of the bottom.

The detail by which all these objects have been attained can only be understood by reference to the plates in connexion with the following description.

We shall confine our attention to the Britannia Bridge, pointing out as they occur any important differences in its Conway model.

Each line of the bridge consists of a single tube, 1511 feet in length, weighing 5270 tons, and, with the exception of the permanent way in the interior, consisting entirely of wrought-iron and cast-iron, viz.

	Tons.
Wrought-iron	4680
Cast-iron	508
Permanent way	82
Total	5270

the cast-iron is entirely confined to those portions of the tube which pass through the towers. This immense beam is supported in five places, viz. on the Britannia Tower at the centre; on each of the side-towers at 460 feet distance on either side; and on the abutments at a distance of 230 feet from the side-towers. It is securely fixed in the centre tower, but its bearings in the side-towers and abutments are movable, that it may expand and contract, from changes of temperature, without resistance.

The lofty abutments with embankments at either extremity continue the permanent way at the proper level for the line. This tube was constructed in four separate portions, the two land portions being built in their places on timber platforms erected for the purpose. The two main portions were constructed on the beach, (*see* Plate I.) The tube marked 3 was placed on the Anglesey side, into the position figured No. 8; and the tube marked No. 1 completed that line. These tubes are now in their place and in use. Tube No. 4 will ultimately occupy the Anglesey side, and tube No. 2 the Carnarvon side, in completing the second line.

These tubes were floated on eight pontoons from the place where they were constructed, deposited at the bottom of the recesses, as seen in plan in Plate V., and raised to their present position by means of hydraulic presses placed in the towers immediately above their extremities; they were then united, not in the position in which they now rest, but in such a manner as to insure nearly the same kind of strain in the towers as though this immense beam had been constructed in one length on a rigid platform across the Straits, and this platform had been subsequently removed to allow the tubes to take their natural deflection. It is evident, that this deflection with the tubes united would be less than the deflection of each individual tube from its own weight; and as it was desirable to preserve the bottom line as nearly horizontal as possible, the tubes were constructed, not perfectly straight at the bottom, but with a rise or camber in the middle of each of about 9 inches, which it was calculated would be about the amount of their deflection when thus united.

The deflection of each tube was found to be about 11 inches, as in the following table; but the union of the tubes in the towers, as hereafter described, has reduced this to about 9 inches.

Tube.	Date of removal of Platform.	Deflection.
		Inches.
No. 1	May 31, 1849	11·72
No. 2	February 11, 1850	10·00
No. 3	May 4, 1849	11·78
No. 4	October 8, 1849	11·16
	Average	11·16

The small tubes also had a trifling rise or camber, so that the whole bridge is very nearly level. The depth of this beam is greatest at the centre, where it passes through the Britannia Tower; its depth is there 30 feet, diminishing towards either end, where it is only 23 feet; the decrease is not in uniform proportion to the distance from the centre, but is more rapid towards the extremities, forming, in fact, at the top a portion of a parabolic curve, with its vertex at the centre tower.

The following table of the depth at different places will illustrate this; and it may be seen also in the elevations in Plates V. and XX.

Over the Britannia or Centre Tower.	At the centre of the Large Spans.	Over each of the Side-towers.	At the centre of the Small Tubes.	Over the abutments or extreme ends.
Ft. in.	Ft. in.	Ft. in.	Ft. in.	Ft. in.
30 0	29 3½	27 2½	25 2	23 0

These are the external depths of the tube; the clear internal height from the surface of the rails to the lowest projection of the castings or plates is about 6 feet 8 inches less than the above heights, the height at the entrance of the tubes being 16 feet 4 inches.

A very illustrative general view of the construction will be found in the isometrical projection at Plate XIII. It will be seen that the top and bottom are each formed of square cells or flues, of sufficient size to allow the workmen to enter them to hold up against the rivets, while they are being inserted, and to cleanse and paint the interior. They are continuous throughout the whole length of the bridge.

The top consists of eight such cells, which are exactly square, being 1 foot 9 inches in height and breadth. The bottom consists similarly of six cells of the same height, but of greater width; their dimensions are 2 feet 4 inches by 1 foot 9 inches.

The sides are plain sheets of plates, stiffened by vertical ribs or pillars of T-iron within and without, and by gussets or corner-pieces, as shewn in the drawing. The sections on Plates XV. and XVI. will further illustrate the construction.

It will be convenient, in describing the tube, to speak first of the bottom, secondly of the sides, and lastly of the top; and to use the letters by which the different portions of the work were distinguished during their formation.

The Bottom of the Tube.

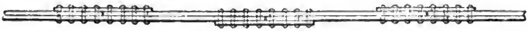
In accordance with what we have before explained, the bottom of the tube may be regarded merely as a chain of plates.

Plate XXI. contains an enlarged section of the bottom, which will be found to consist of two platforms of plates marked **D**-plates and **E**-plates; these are connected by a series of seven vertical plates marked V-plates. It will be seen, moreover, that the D and E platforms are each composed of two layers of plates. A reference to the plan of the D and E platforms, in Plates XV. and XVI. will shew that the plates are arranged in six parallel rows; those in the four inner rows are 2 feet 4 inches wide. In the outer rows they are 4 inches wider, to afford a better attachment for the sides. The whole of these plates are 12 feet long; the variations in their thickness are figured in Plate XX. They consist of two layers, as before observed, the dotted lines representing the joints in the lower plates, and the plain lines those in the upper layer.

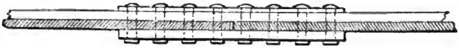
The arrangement and thickness of the V, or vertical plates, are also shewn in the same plates. These plates are also 12 feet long and 1 foot 9 inches in height, arranged singly. The thick lines and the small circles on Plate XX. indicate the places where the variations in thickness occur.

The thickness of the whole of the plates at the centre of the large span is nine-sixteenths of an inch, diminishing to six-sixteenths of an inch in the small tubes, except the two outer V-plates, which are placed immediately beneath the sides, and maintain a constant thickness of ten sixteenths of an inch throughout the large tubes, and nine-sixteenths of an inch in the small tubes.

The longitudinal connexion of the bottom plates was manifestly a consideration of the greatest importance. In the first Conway Tube, in accordance with the original drawings, the plates were connected in the manner shewn in the following sketch; in which it will be observed that the plates

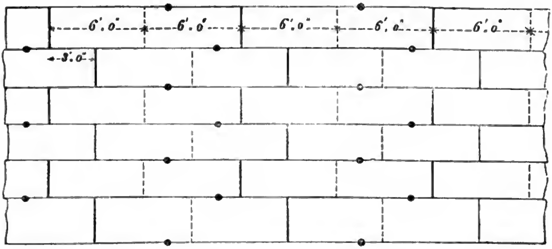


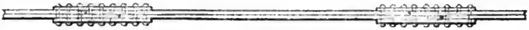
which form the upper layer are lapped 6 feet, or half their length, over the lower ones, so that there is a joint exactly opposite the centre of each plate, the joint occurring alternately in the upper and lower series. To maintain a proper connexion at the joint, a short plate termed a "cover," of the same thickness as the plates, is riveted over the joint, the rivets passing through both layers of plates as well as through the cover. Now it is evident, in this arrangement, that when a tensile strain is induced in the bottom, the tendency of the joint in either layer to separate is resisted only by the rivets, which bear partly on the cover and partly on the adjacent plate; and whatever be the amount of strain thus imposed on the unbroken plate, it is evidently additional to the strain which is naturally sustained by that plate from its own position; and this increased strain occurs at the very point where the plate is perforated by the rivet-holes, which are necessary for the attachment of the cover. To remedy this defect, in the second tube at Conway, and in the large tubes at the Britannia, an additional cover, half the thickness of the plates, was riveted over each joint, opposite the original cover. The figure below represents this arrangement, in which it is evident that the rivet has to be sheared in two places, and is consequently rendered more efficient, without throwing extra strain on the plate which crosses the joint.



The six rows of double plates thus connected longitudinally are so arranged side by side, that the corresponding joint in each alternate layer is 3 feet in advance of that in the three neighbouring layers, as in the following sketch, in which the black lines represent the joints in the upper layer, and the dotted lines those in the lower layer.

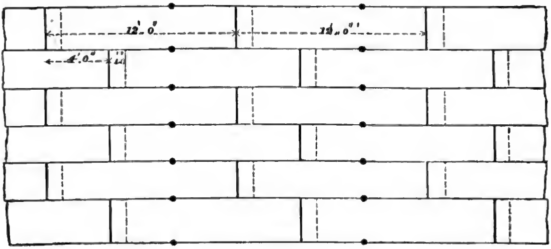
This arrangement, which is adopted both in the **D** and **E** platforms, will at first sight appear very perfect, as the joints are uniformly distributed, and consequently as remote from each other as possible; but it possesses this disadvantage, that when the two platforms are connected by the vertical plates to form the complete bottom of the tube, the joints become so numerous and so near to each other, that it is not difficult to trace a *weak section*, or line of ultimate fracture, extending from rivet-hole to rivet-hole, and allowing a complete separation at the bottom, without having to traverse in any parts of its course that portion of the plates which is not weakened by rivet-holes. This defect was remedied in the portions of the bridge last constructed, viz., the small tubes, by a different kind of joint, which is figured below.





In this joint the upper layer is lapped one foot in advance of the lower layer, and over this junction, which occurs but once in every 12 feet, a pair of covers is riveted, one on either side; these covers are 3 feet in length and contain nine rivets in each row.

The joints in each alternate row are placed 4 feet in advance of those in the neighbouring row; and in the intervening spaces of 8 feet, the joints of the V, or vertical plates, are arranged in a transverse row across the bottom, as indicated by the circles in the following figure; they are connected



by a pair of 2 feet 8 inch covers, as in the large tubes. A careful study of the above arrangement will shew that in any ultimate fracture of the bottom the line of rupture must necessarily pass through some of the plates in parts which are not weakened by covers.

By this arrangement, also, the use of the extra covers before described is rendered unnecessary, and the number of rivets in the joints reduced in the proportion of 18 to 32. It offers, moreover, some additional facilities to the workmen in plating the cells.

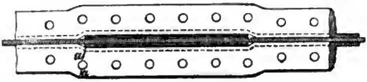
It will be observed, in Plates XV. and XVI., that the rivets in the covers are arranged in longitudinal rows in accordance with the erroneous reasoning alluded to at page 519; this longitudinal arrangement, however, affords facilities for punching the plates by the rack and traversing table; and the work was too far advanced to render any alteration in this respect desirable, but it will be seen, nevertheless, by the experiments on riveting, in which the great importance of *friction* is made manifest, that zig-zag or diagonal riveting, as employed in the X-plate covers at Plates XVII. and XXI., would have been decidedly stronger.

Reverting to the large tubes, the covers used in the bottom are of three kinds. Their length is uniformly 2 feet 8 inches, but they vary in breadth. Those *within* the cells, on the upper side of the E-platform, and on the under side of the D, are the full width of the cells, 2 feet 4 inches. The edges are cranked over the angle-iron on each side, the rivets passing through both, as shewn in the section Plate XXI. There are also two rows of rivets down the centre of each cover, eight rivets in each row.

The covers on the outside of the cells, *i. e.* on the upper side of the D-platform and under side of the E, are 8 inches wider than those within the cells, for they not only embrace the transverse joint which they are more especially designed to cover, but extend laterally 4 inches over the contiguous longitudinal plates on either side, where they are secured by the rivets which pass through the angle-iron in the neighbouring cells, (*See* Plate XVI. "D-*platform.*") They thus perform an important office in the connexion of the several rows of plates laterally; their dimensions are 2 feet 4 inches by 3 feet, and their thickness, like that of the inner covers, is in all cases the same as that of the plates which they unite.

The V-covers, or those which connect the vertical plates, having only to cover the joint of a single plate, are used in pairs, one on either side of the joint, each cover being half the thickness of the connected plate; their depth is 1 foot 9 inches, the same as that of the cells; they are cranked over the angle-iron at the top and bottom in the same manner as the E-covers. A V-cover is shewn in Plate XXI., and also in the section of the lower cells in the same Plate.

In the bottom of the first Conway Tube, instead of cranking the covers over the angle-irons, as just described, the angle-iron was cranked over, the covers being bent horizontally at every V-cover and vertically at every D or E-cover. This very objectionable plan was, however, speedily abandoned; as, independently of the expense and difficulty of bending such an awkwardly-shaped material as angle-iron, it was frequently found that the bars were cracked at the point of flexure, as at *a a* in the following figure, and were in all cases much damaged by the operation.



The angle-iron, moreover, being in a state of tension, it was important that it should be kept as straight as possible for the more direct transmission of the strain. The crank in the cover avoids all these objections, and is quickly formed by a single blow from a stamping press, or double swage, weighing about a ton, which is allowed to descend from some height upon the cover, while it is red-hot.

At those parts of the tubes which rest upon the bed plates the covers are omitted in order to leave a smooth surface for the tube to rest upon; their place is supplied by an extra layer of plates half an inch in thickness and the full breadth of the tube, into which the heads of the rivets are countersunk.

The corners of the cells throughout the tube are occupied by angle-irons, which serve the double purpose of uniting the plates, and increasing the sectional area of the bottom. For this object the joints are covered by a short piece of angle-iron 16 inches in length, which is riveted over the spot, as in Plate XXII. The whole of the rivets in the bottom are arranged in longitudinal rows at a distance of 4 inches asunder. They are all fifteen-sixteenths of an inch in diameter, except the two rows down the middle of each cover; these are $1\frac{1}{8}$ inch in the large span, and $1\frac{1}{16}$ inch in the small.

All the arrangements described are designed more especially to resist longitudinal strains, and no provision has been alluded to for giving stiffness to the bottom crosswise, or to obviate its tendency to become deflected along the middle by the weight of the permanent way and trains; this tendency is resisted, however, by a series of transverse plates placed on edge, which reach entirely across the floor of the tube, and are secured to it, and also to the side by a pair of angle-irons. These plates are 10 inches in depth and half an inch in thickness; they occur every 6 feet throughout the tube, and are termed *cross keelsons*. The longitudinal timbers of the permanent way are supported upon these keelsons by brackets of angle-iron 16 inches in length, as shewn in the section at Plate XVI. They are also used in the top of the tube where they are placed 12 feet asunder, over each alternate one in the bottom.

The bottom of the tube may be regarded, therefore, as a chain of thirty-one plates, united by twenty-eight angle-irons, all of which are continuous from end to end of the bridge, except in the small tubes, where, in consequence of the D-platform having only a single layer, the number of plates in the section is reduced to twenty-five. The floor-plates are all 12 feet in length, 2 feet 4 inches or 2 feet 8 inches in breadth, and from $\frac{6}{16}$ths to $\frac{9}{16}$ths of an inch in thickness. The vertical plates are also 12 feet in length, 1 foot 9 inches in depth, and from $\frac{6}{16}$ths to $\frac{10}{16}$ths of an inch in thickness.

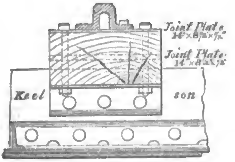
The angle-iron is of uniform size throughout; it has an average sectional area of 2·7 square inches, and weighs about 9 lbs. per lineal foot. A full-sized section of it is shewn in the right-hand corner of Plate XXII. The heaviest plates used in the tube are those in the bottom. Some of the larger sizes weigh 6½ cwt. each, and a few have weighed as much as 8 cwt.: these were 14 feet 6 inches long × 2 feet 8 inches wide.

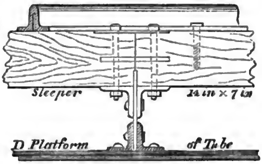
The total weight of wrought-iron in the bottom of one entire line of tubes is 1472 tons. Of this quantity about 965 tons are in the form of plates, and 217½ tons are angle-iron. The requisite covers for connecting the plates and angle-iron longitudinally weigh 237½ tons, so that the weight of the bottom of the tubes is increased by upwards of 19 per cent, in consequence of the want of continuity in the plates (or 24½ per cent, if we include the weight of the rivet-heads): the heads of the rivets, which are about 249,000 in number, make up the remaining 52 tons.

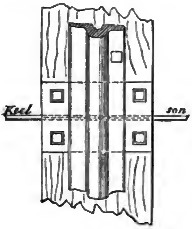
The Permanent Way.

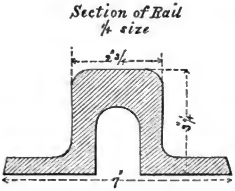
The permanent way is laid through the tubes upon the transverse keelsons, which occur at distances of 6 feet throughout the bottom, as shewn in Plate XV. Longitudinal balks, 14 inches by 7 inches, as in Plate XVI., are inserted throughout the whole length of the tube; and to ensure a bearing on these vertical plates, it will be observed that two pieces of angle-iron are riveted opposite each other on each keelson, the timber being notched to receive the keelson, and secured by bolts passing through it and the angle-iron.

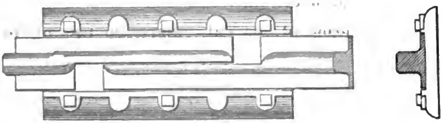
The ordinary flanged-rail with chairs is shewn in Plate XV. as employed at Conway; but in the Britannia Bridge a rail similar to the Great Western rail, commonly called a bridge-rail, and requiring no chairs, has been used. The section of this rail and of the timber supporting it, with the means employed for securing the longitudinal timbers end to end, are shewn in the following sketches. At each extremity of the tube the expansion and contraction, without some provision for that purpose, would separate the rail in the permanent way, through a space amounting at times to 3 or 4 inches. To remedy this, at each extremity of the tube an expansion-rail is introduced, as in the sketch below. Each half of the divided rail is secured in contact with the other half, but is at liberty to move lengthwise. This produces a slight increase of guage for a few inches in this position; and an internal guard-rail has been applied at Conway to obviate











any accident from this cause; but at the Britannia Bridge these expansion-joints are not placed immediately opposite each other, but are 6 feet apart: the guard-rail is thus rendered unnecessary.

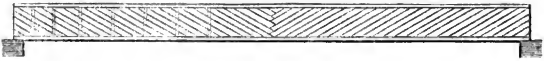
On account of the extreme rigidity of the tube the jar occasioned by the passage of trains has been found liable to loosen the spikes by which the chairs are attached to the sleepers, and also the screw-bolts by which these latter are attached to the keelsons; although, to give additional elasticity to the permanent way, the chairs in the Conway Bridge have not been placed immediately over the keelsons, as shewn in the Plate, but 2 feet on either side.

The flanged-rails in the Britannia Bridge are riveted together by a quarter-inch plate under each joint, and secured to the timber by fang-bolts passing through the sleeper.

To admit sufficient light for the examination of the permanent way, and for passing conveniently through the tubes at the Britannia Bridge, round holes, 4 inches diameter have been pierced, at intervals of 12 feet, through the side-plates; these holes are glazed to exclude the wet.

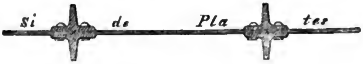
The Sides.

The sides may be considered, in accordance with wha we have stated, as a system of trellis or lattice-work, in con nexion with a series of vertical pillars, connecting togethe the top and the bottom of the tube. The strain they hav

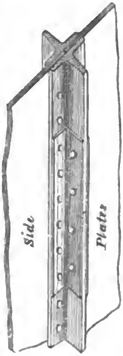


to resist is more especially a diagonal strain, and it would probably have been better, had it not been inconvenient in practice, to have arranged the plates diagonally, as shewn in the sketch above. The pillars would then have crossed the joints obliquely.

It was, however, preferable in practice to make the joints vertical. The sides are, consequently, formed of a series of plates 2 feet in width, and of varying height; their edges are butted against each other, and are embraced by two vertical pillars or ribs of T-iron placed face to face, as sketched below, and as figured full size in Plate XXII.



The T-irons reach from top to bottom both outside and in. The two flat surfaces of the T-irons may be regarded as covers uniting the plates, while the ribs projecting at right angles give depth and stiffening as a pillar. The height of these pillars, one of which occurs every 2 feet, varies from 19 to 26 feet; and as it was found difficult to procure T-iron of sufficient length to form it in one piece, it was necessary to have joints, which are, however, stiffened by a pair of short lengths of angle-iron riveted over the joints. A sketch of a joint so covered is given, and a full-sized section of the covering angle-iron is given in Plate XXII. On the outside of the tube the T-iron is cranked over the angle-iron which unites the sides to the top and bottom, the ends butting upon the floor-plates, as shewn in Plate XXI.; but in the inside of the tube the T-iron is curved round at a right angle into what is termed a *knee*, and is continued horizontally across the floor of the tube 2 feet 8 inches at bottom, and 3 feet 6 inches at top, and there securely riveted (Plates XV. and XXI.); the angle of



the knee is filled up by a pair of triangular plates termed *gusset-plates*, riveted one on either side of the rib of the T-iron. This kind of joint was not, however, deemed sufficient for the stiffening and connexion of the sides at the ends of the tubes. For a distance, therefore, of 40 or 50 feet from the towers a stronger kind of pillar is used; it is formed of four angle-irons of the strongest section, placed face to face, assisted by a pair of quarter-inch strips, riveted on either side of the joint beneath the angle-irons, as shewn full size in Plate XXII. and in Plate XXI. In addition to these there are two strips placed at right angles to the sides termed *stiffeners;* one of these on the outside is the same breadth as the angle-irons, and is wholly embraced between them; the other one within the tube is 9 inches in breadth, and projects 5 inches beyond the angle-irons, offering a direct resistance to any bending of the sides. Similar stiffeners occur also at intervals of 12 feet throughout the large tubes. The distances to which the angle-irons extend beyond the towers is best shewn in the General View, Plate XX., where they are indicated by double lines.

We come now to the side-plates themselves, which are uniformly 2 feet in breadth, and usually either 6 feet 6 inches or 8 feet 8 inches in length. Their disposition is shewn in Plates XIII. and XIV., in which it will appear that the rows consist, alternately, either of three short plates or four long plates, with a longer or shorter piece at the top, to conform to the varying height of the sides; these short pieces are called *variables.* A slight departure from this arrangement is made in the small tubes, as is shewn in Plate XX., where an elevation of the side-plates in one-half of the bridge is given. The thickness of the side-plates is indicated on the same drawing. It will be there seen that the plates are half an inch thick at the centre, but are increased in thickness towards the ends, a circumstance the reverse of what might at first sight be expected; but it must be remembered, that both before, and especially after the junction of the several tubes over the towers, the weight of the bridge is supported at the ends by the side-plates alone, the top and bottom cells being efficient only in resisting a horizontal strain; and were it not for the thickness of the plates at this part, and the stiffened pillars of angle-iron before described, the sides would invariably become disrupted at the ends.

The thickened plates extend then across each tower, and for a considerable distance on either side, diminishing gradually from $\frac{10}{16}$ths to $\frac{9}{16}$ths and $\frac{8}{16}$ths. A few rows of plates at the extreme ends of the large tube are made three-quarters of an inch in thickness, for the more secure attachment of the lifting castings. At the centre of the small tubes half-inch plates are used, as in the large ones, for it was not considered prudent to expose a thinner plate to the action of time and the weather.

The ends of the plates are connected by a pair of covers half the thickness of the plates placed over the joint, one on either side. Where the T-iron is used, the covers are *joggled* over it, and the rivets pass through both, as shewn in Plate XIII., and in the right hand "side-plate covers," Plate XXI.; but at the angle-iron joints the covers are shorter, and are let in between, as in Plates XIV. and XXI.; they have a single row of rivets in both cases.

The gussets, to which allusion has already been made, constitute a prominent feature in the tubes, as they recur at every joint throughout the bridge, both at the top and bottom, and upon them devolves the important office of retaining the whole structure in shape, and preventing twisting or distortion; they are, at the same time, most efficient auxiliaries in connecting the sides with the top and bottom.

The triangular plates of which they are composed are always used in pairs, which are riveted one on either side of the rib of the ┬-iron; a narrower strip, of the same thickness as the rib, is riveted diagonally between them. Their ordinary height is 2 feet, their base 15 inches, and their thickness either $\frac{4}{16}$ths or $\frac{5}{16}$ths. This, the ordinary or most simple form of gusset, is shewn in the third figure at Plate XXI. Several modifications of it are rendered necessary where the angle-iron joints and cross keelsons occur, which it is not necessary to detail. In the large tubes, however, when the height of the sides is very considerable, gussets of extra size are used at certain intervals. The largest of these are 5 feet high by 2 feet base; the next in size are 4 feet by 1 foot 9 inches; and a smaller size is 3 feet by 1 foot 3 inches. All of them are $\frac{5}{16}$ths in thickness.

The largest or 5-feet gussets are used only at the high end of the large tubes, near the Britannia Tower. For the first 8 feet from beyond the towers, on either side, they are used at every joint, their rigidity rendering them very serviceable in opposing any tendency to distortion from the severe and peculiar strain to which the sides are exposed at this part. The next four large gussets are placed at intervals of 6 feet, one on every keelson, the intermediate spaces being occupied by the ordinary small-sized gussets; beyond this they occur at intervals of 12 feet, on every alternate keelson. At about 100 feet from the tower the large gussets are discontinued, and their place is supplied by the 4-feet gussets, still 12 feet apart; and at 230 feet the 3-feet gussets are substituted; these extend to within 58 feet of the opposite tower. At this point, however, the 4-feet gussets are again resorted to, and, as the tower is approached, they recur more and more frequently, in the same manner as at the Britannia end. These gussets are invariably used at the top as well as the bottom, and in connexion with the cross keelsons at the top and bottom of the tube, and the 9-inch stiffening plates, which are attached to the sides, as before described, they form a complete frame or diaphragm within the tube every 12 feet, of great stiffness, and admirably calculated to resist distortion. In the land tubes the extra-sized gussets were not deemed necessary; the ordinary 2-feet gussets are, therefore, used throughout. Four different modes of their attachment are shewn in Plate XXI. The two left-hand figures represent the modifications used near the ends, where the side-plates are connected by double angle-irons with stiffening-plates.

The third variety is the ordinary curved T-iron knee and small-sized gussets before described, which is used both in the large and small tubes. In the right-hand figure the connexion of a large gusset with a keelson and T-iron is shewn.

The sides are connected with the top and bottom cells in the manner shewn in Plate XXI. A pair of stout angle-irons, 4½ inches in section, is secured along the lower edge of the side by a row of rivets 3 inches apart, and each of the angle-irons is attached to the bottom-plates by another row of rivets, one within the tube and the other without; these last-mentioned rivets pass down through the plates and covers of the D-platform, and through the angle-iron within the bottom cells; they are the longest rivets used in the tube, and in many places they traverse six layers of iron, having an aggregate thickness of nearly 3½ inches, they are 1⅛ inch in diameter, and are placed 4 inches apart. The intervals between the covers and the D-platform are packed up level with the covers, so that the connecting angle-irons are kept perfectly straight.

The connexion with the top is more simple, but is effected in a similar manner, and in both cases the ends of the outside T-iron pillars are cranked over the angle-irons, and riveted to them. Allusion has already been made to the additional assistance rendered by the knees and gussets in the connexion of the sides.

Considerable care was taken to ensure contact between the vertical edges of the side-plates, which was done in many cases by driving in narrow strips of wrought-iron; the rivet-holes were also carefully rimered smooth before the insertion of the rivets.

The sides, or, as they may be termed, the *vertical rib*, of this great tubular girder, consist, therefore, of two sheets of plates, from half to three-quarters of an inch in thickness, connected and stiffened by pillars of angle and T-iron, and gussets. The weight of this portion of one line of tubes is about 1727 tons, a weight greater than that of either the top or bottom. We find from the table of wrought-iron, at page 587, that this amount is made up of 938 tons of plates, 607 of angle and T-iron, 113 tons of rivet-heads, and 68 tons of covering-plates; this table, however, although tolerably correct, so far as regards the top and bottom of the tubes, becomes very fallacious when applied to the sides, for some considerable portions of the T and angle-iron pillars are evidently performing the functions of covers in maintaining the connexion of the plates, while other portions are engaged as pillars and in stiffening the sides, the proportion of plates is also too large. It may be interesting, therefore, to analyse the sides of one of the large tubes, weighing about 596 tons, and to separate them into their component parts to observe their respective proportions. The results, which have been carefully calculated, are given in a tabular form.

It may be observed, that the disproportionate weight of the sides is due to several causes—to the large gussets, to the number of rivets, to an accidental error in punching some of the thicker plates, which necessitated their use in a part for which thinner plates had been designed, but principally to the increased strength given to the vertical angle-iron joints near the ends. The material in the sides of one large tube is distributed in the following manner:—

	Tons	cwt.	Per Cent.
Plates acting as sides	237	0	40
Plates, &c., acting as covers	114	15	19
Pillars and stiffeners	162	3	27
Knees and gussets	40	15	7
Rivet heads	41	1	7
	595	14	100

The *plates*, which constitute 40 per cent of the entire quantity, consist only of the simple sheets of side-plates, without T-irons or covers. The *covers*, which amount to 19 per cent, include those portions of the T and angle-irons which are indispensable for the connexion of the plates. In the bottom and top of the tube the covers constitute 16½ and 6½ per cent respectively.

Under the head *pillars* and *stiffeners* are included all the remaining portions of the angle and T-irons, together with the stiffening-plates, which are placed at right angles to the sides, and all those portions which are requisite as pillars, or for stiffening and keeping the sides in shape; these portions constitute 27 per cent. The knees and gussets, which are kept separate, form the remaining 7 per cent.

There are about eighteen miles of T-iron and angle-iron in the sides of the bridge (in one line); the number of rivets is 535,650.

The Top.

The top of the tube consists of eight cells, each 1 foot 9 inches square, these cells being formed by two horizontal layers of plates, united by nine vertical divisions, which form the sides of the cells; the latter are marked X-plates in the section at Plate XXI., and the upper and lower layers are called A and B-plates respectively.

In general appearance the top resembles the bottom, but in construction it is quite distinct. The A and B-platforms are single, instead of double, as in the bottom; and the plates are only 6 feet long, instead of 12; they are, however, much thicker, and the connecting angle-irons are heavier, so that upon the whole the sectional area exceeds that of the bottom.

As the A and B-platforms are exact counterparts of each other, one description will suit both. The plates which compose them are arranged side by side in eight parallel rows, the plates in each row being 1 foot 9 inches broad, corresponding to the dimension of the cells; those in the outer rows are 4½ inches broader, to allow room for the two rows of rivets which connect them to the sides. (*See* section at Plate XXI., also XVII. and XVIII.) These longitudinal rows are connected together, and also to the vertical plates, partly by the angle-irons which occupy the corners of the cells, and partly by a series of 9-inch plates of iron half an inch thick, which are riveted over the joints, extending longitudinally from end to end of the tube, on the top of the A-platform and underneath the B. These strips will be recognised in the plates above-mentioned, and also on the projection at Plate XIII. The ends of the plates butt against each other in close contact. The joints are united by a pair of short covers, one on either side the joint, which are let in between the longitudinal strips, and are fixed by six rivets, three in either plate, as shewn in Plate XIII. The top of the tube consequently presents the appearance of a series of sunken panels, about 1 foot broad and 5 feet long. The thickness of the plates follows the same general law in the bottom,—it is at a maximum in the centre of the span and over the towers, and is diminished at the intermediate positions. In the large tubes all the plates at the centre are $\frac{12}{16}$ths inch thick; these are the stoutest plates used in any part of the bridge; over the towers they are $\frac{11}{16}$ths thick. For the thickness at other parts the reader is referred to Plate XX.

The **X**-plates are of the same thickness, and are united by covers in a precisely similar manner to the **A** and **B**-platforms. A glance at the section of the upper cells in Plate XXI. will fully illustrate the construction of the top.

The top in its general design is treated as a pillar; thus very much care was bestowed on the butt joints of the top plates to ensure close contact, although the covers over the same joints are smaller than in any other part of the tube, and, as just observed, contain only six rivets. An important modification, however, takes place in the covers as they approach the ends, for it is evident that over the towers and in their immediate neighbourhood a powerful tension is excited, which is even greater than that in the bottom of the tube at the centre. This severe strain is induced by the process of lowering the opposite extremities of the tubes after they have been connected together over the towers.

The length of the covers, therefore, at these parts is increased from 8 inches to 1 foot 9 inches, and the number of rivets is also increased from six to sixteen or eighteen. These extra-sized covers are shewn in Plates XVII. and XVIII., and one of them is drawn to a large scale in Plate XXI. They extend about 90 feet on either side of the towers, passing into the ordinary covers through a transition size of 16 inches, with 12 rivets. Their precise range is noted in the plan in Plate XX. The covers of the **A**, **B**, and **X**-plates all follow the same law; they are in all cases half the thickness of the connected plates, and are used in pairs.

At intervals of 12 feet throughout the length of the tube transverse plates, or "*cross keelsons,*" are riveted across the top, and are connected to it by angle-irons, as before described, in the bottom, where they occur at intervals of 6 feet; each of these is 10 inches deep, and is connected to the sides by one of the extra large gussets. The angle-iron used in the top has a sectional area of 4½ square inches, and weighs 45 lbs. per yard. There are about 12 miles of it in one roadway. The number of rivets is about 310,000; they have but few thicknesses of plates to pass through, and the construction of the top is altogether simple and inexpensive.

The total weight is 1481 tons; the plates weigh 974 tons, the angle-irons 341, the covers 102, and the rivets 64 tons. The proportion of the covers is thus less than 7 per cent, while in the bottom it amounts to 16, and in the sides to 21 per cent. In the Conway Tubes, where the top has no tensile strain, and consequently no long covers, they do not constitute much more than 3½ per cent on the entire weight. It is, doubtless, this comparatively small proportion of weight required for the connexion of plates in a state of compression that has led to the economical employment of wrought-iron in bow-string bridges and arches, and other structures in which wrought-iron is only subjected to compression, and has brought it into successful competition with cast-iron, a material whose power of resistance is five times as great, and in value materially less; but the means of connecting such a material by flanges are necessarily cumbrous and expensive.

General Summary—Britannia Bridge.

For convenient reference the weight of a single line and the number of rivets are repeated in a tabular form, together with the sectional areas at the centre of the large tubes.

	Weight.	Sectional Area.	Number of Rivets.
	Tons.	Sq. Inches.	
Top	1481	648·25	310,390
Sides	1727	302·00	535,650
Bottom	1472	585·43	249,010
	4680	1535·68	1,095,050

The entire bridge, including both lines, contains nearly a million and a half cubic feet, or 105,000 tons of masonry, 44,200 cubic feet, or 9480 tons of wrought-iron, and 1988 tons of cast-iron.

The two tubes in their complete state contain 9360 tons of wrought-iron, 1015 tons of cast-iron, and 165 tons of permanent way. They are composed of about 186,000 separate pieces of iron, pierced by seven millions of holes, and united by upwards of two millions of rivets. They contain 435,700 feet, or eighty-three miles of angle-iron; and their total weight is 10,540 tons.

Method of Construction.

The bottom of the tubes was in all cases laid down and riveted *in situ* on a platform. As soon as the first portion of rivets had been introduced, the supports were shifted a little aside, by loosening the wedges and the remaining rivets inserted. The top also, after the sides were erected, was formed in a similar way, the transverse plates, or keelsons, forming a scaffolding on which the horizontal platforms were laid, but the sides were constructed at a distance in detached portions, weighing two or three tons, and each consisting of four rows of plates, partially riveted together, the outer T-irons being of the full length, but the interior ones four feet too short both at top and bottom, this space being subsequently filled up by the vertical portion of the knees. In this state these detached portions were numbered and laid aside until required; they were then removed on trollies, and raised into their places by travelling-cranes, which bestrode the tube, and traversed its whole length on rails laid on either side. One of these admirable machines forms a conspicuous feature in the foreground of Plate III. The contrivance shewn on the top is called a "travelling monkey," it is a block with three sheaves, rolling upon wheels, and the weights suspended from it can be either raised, or lowered, or traversed from side to side, at the will of the operators, who are stationed at a winch at the foot of the machine on each side. A weight of 5 or 10 tons is readily lifted and transported over any part of the tube by one of these cranes.

The tubes being nearly as broad and as high as the openings in the towers, for which they were designed, it was evidently not practicable to build them in their places, and the following contrivances were resorted to. A portion of the extreme ends of the small tubes, 14 feet in length, was constructed outside, upon the timber platform, and launched in entire into the abutments, by sliding it down inclined "ways" of hard wood lubricated with tallow and soft soap, in the same manner as a vessel is launched. The intervening space was subsequently filled in and the tube made perfect. In the side-towers a still larger portion, 28 feet long, and weighing 170 tons, was constructed outside the towers; and when the large tube was raised to some distance above its permanent level, the piece was advanced forward and united to it. The temporary supports were then knocked away, and the expansion rollers having been adjusted, the tube and its additional piece were quietly lowered down by the presses to a permanent bed of creosoted timber, anointed with a pasty mass of red and white lead; the junction with the remainder of the small tube was then conveniently effected in the open air. It was necessary to have recourse to a different plan in the Britannia Tower, which had no scaffolding on the outside, on which to construct the junction-pieces. They were here constructed just as if the tube had only four cells instead of six: the two halves were then separated laterally, and the two centre cells inserted between them.

Two separate pieces, 8 feet in length, were here constructed, one of which was connected to the ends of each of the large tubes, and the whole lowered on to the permanent bed. The final connexion of the tubes was effected by filling in the gap between these two portions of the bridge. For this purpose three recesses were left in the stonework on either side, 2 feet deep, and from 4 to 6 feet broad, opposite the junction places which gave the necessary access to the work. These recesses are shewn on the plans of the towers at Plate VIII., &c. The tubes are 9 feet asunder. The top of each tube forms a platform nearly 15 feet wide; and as the stone lintels do not come close to the tube, there is a convenient passage entirely across the bridge. The plates are all "caulked," or rendered water-tight, by upsetting the iron in the joints with a blunt chisel, and the exterior is painted with light stone colour by means of a suspended stage travelling along the tube on wheels.

In the interior a convenient pathway of planks is laid throughout, and there is ample room to stand on either side during the passage of a train. A sombre light is admitted through a series of circular holes, 4 inches diameter, which are pierced through the side plates on one side of the tube at intervals of 12 feet, and glazed with plate glass. A trapdoor in the side affords convenient access to the centre tower, and man-holes are opened into each of the cells, and to the bed-plates and rollers of the side-towers, so that all parts of the work are easily accessible.

It is intended to protect the bridge, when complete, by a light arched roof of galvanised iron, covering both the tubes, and to connect them together at intervals by light pillars of T-iron, and thus enable them to offer a joint resistance to the wind.

The Conway Tubes.

The foregoing description will apply almost equally well to the Conway Bridge and the Britannia. There are the same number of top and bottom cells, and they are of similar dimensions. In the double layers of the bottom platforms, and single layers of the top, in the sides growing thicker and stiffened by angle-iron at the ends, in the dimensions and disposition of the plates, in the arrangement of the rivets, and, in fact, in their whole construction, they are almost exact counterparts of each other. We will, therefore, enumerate only those points in which they differ, and these dissimilarities are occasioned almost entirely in consequence of their not being continuous beams, as in the Britannia, but simple and independent tubes. The clear span of the Conway Bridge is 400 feet, or 60 feet less than the large span of the Britannia; the tubes, as constructed and floated, were 412 feet long, having a bearing of 6 feet at each end. Subsequently a short piece 6 feet in length was added to each end; so that its entire length is 424 feet, allowing a bearing of 12 feet in either tower. The Conway end is bedded firmly on the masonry, but the opposite extremity rests upon rollers and gun-metal balls, as at the Britannia, to allow freedom for expansion during changes of temperature. The greatest increase of length from this cause hitherto observed has not exceeded an inch. The tubes are highest at the centre of the span, where their external depth is 25 ft. 6 in.; thence it diminishes gradually towards the ends, where it is 22 ft. 6 in., or six inches less than at the Britannia; the breadth is the same in both bridges; there is an interval of 9 feet between the tubes, which are not in any way connected together; the height of the bottom above high-water is about 17 feet, while at the Menai the tubes are 103 feet. The most important distinction will, however, be found in the thickness of the plates at the top and bottom, as marked in the General Plan at Plates XL. and XLI. It has been already observed that the Britannia tubes have thicker plates and longer covers within and near the towers, in order to withstand the strain caused at those parts by uniting and lowering the tubes; but in the Conway, where this cause is not in operation, it will be seen that the plates become progressively thinner towards the ends, both in the top and bottom, although not in the sides, and all the covering plates in the top are short and with few rivets; the variations in thickness can be best studied on the plan. The permanent way is laid on transverse keelsons, as in the Britannia; the gussets are all small, or 2-feet gussets. The total weight of wrought-iron in one of the Conway Tubes is 1180 tons, of cast-iron 101 tons; the wrought-iron in one of the tubes 412 feet long, as floated, without the extra pieces at the ends, is 1147 tons. The following analysis will shew pretty correctly in what manner the different portions of this metal are employed:—

Top.

	Tons	cwt.
Plates and angle-iron in compression	336	0
Plates and angle-iron acting as covers..............	17	8
Transverse keelsons	7	0
Rivet-heads	22	7
	382	15

Sides.

	Tons	cwt.
Plates acting as sides	163	0
Covers and proportion of T-iron acting as covers	90	10
Gussets, stiffeners, and projecting rib of T-iron engaged in stiffening the sides	101	16
Rivet-heads	23	15
	379	1

Bottom.

	Tons	cwt.
Plates of angle-iron in tension	279	9
Plates and angle-iron acting as covers	76	6
Transverse keelsons	14	0
Rivet-heads	15	17
	385	12
Total	1147	8

It will be observed from this table how small a proportion the covers in the top bear to those in the bottom and sides, although the weights of those several parts are very nearly equal. In fact, by a coincidence, the weights of the top, bottom, and sides of the complete Conway Bridge, are almost exactly identical, as is shewn by the table at p. 588; the same equality does not, however, obtain in the Britannia Bridge. Each of the Conway Tubes is covered with a light arched roof of galvanised tissue-iron, to protect it from the weather. They are painted inside and out with light stone colour.

TABLE I.—*Tabular Summary of Wrought-iron Work in the Britannia Bridge.*

	TOP OF TUBE.			SIDES OF TUBE.			BOTTOM OF TUBE.			GENERAL SUMMARY.		
	One large Tube, length 470 feet.	One small Tube, length 242 feet.	One Roadway, complete length 1511 feet.	One large Tube, length 470 feet.	One small Tube, length 242 feet.	One Roadway, complete length 1511 feet.	One large Tube, length 470 feet.	One small Tube, length 242 feet.	One Roadway, complete length 1511 feet.	One large Tube, length 470 feet.	One small Tube, length 242 feet.	One Roadway, complete length 1511 feet.
	Tons.	Tons.	Tons.	Tons.	Tons.	Tons.	Tons.	Tons.	Tons.	Tons.	Tons.	Tons.
Plates	322	143	974	316	127	938	334	121	965	971	391	2877
Angle or T-iron	113	48	341	215	75	607	67	35	218	395	158	1165
Covers	32	16	102	24	9	68	83	30	238	139	55	408
Rivet-heads	22	9	64	42	12	113	18	7	52	82	27	229
Total	489	215	1481	597	221	1727	501	193	1472	1587	630	4680

	Length.	Weight.	Tons per Foot run.
	Feet.	Tons.	
One large span, clear length between supports ..	460	1553	3·38
One small span, clear length between supports ..	230	600	2·6
One roadway complete	1511	4680	3·1
Both lines complete	3022	9360	6·2

Exact length of one line at 32° Fahrenheit, 1510 feet $2\frac{1}{2}$ inches.

TABLE II.—*Sectional Area and Depth of the Tubes.*

BRITANNIA BRIDGE.

Distance from entrance small Tube.	Top.	Sides.	Bottom.	Total.	Outside depth at these points.	
Feet.	Sq. inches.	Sq. inches.	Sq. inches.	Sq. inches.	Ft.	in.
0	513·00	285·625	375·875	1174·50	23	0½
42·5	534·50	240·312	375·875	1150·687	24	0¼
85	556·49	248·810	408·00	1213·30	24	8¾
Centre small span.	580·50	254·560	414·55	1249·61	25	2½
85	556·49	260·62	414·55	1231·66	25	8½
42·5	580·50	301·50	378·91	1260·91	26	4½
Land tower.	592·49	345·31	359·766	1297·566	27	0¼
50	570·625	357·50	488·12	1416·24	27	9½
100	591·185	328·50	533·24	1452·92	28	4
150	618·89	296·0	545·37	1460·26	28	9
200	648·25	300·	585·43	1533·68	29	5¼
Centre large span.	648·25	302·	585·43	1535·68	29	3½
200	641·37	304·	585·43	1530·80	29	5½
150	607·02	308·	533·24	1448·26	29	8¼
100	591·185	349·975	510·12	1451·28	29	10¼
50	603·05	390·	488·12	1481·17	29	11½
Centre Brit. tower.	618·89	468·	575·24	1662·13	30	0

No deduction made for rivets.

TABLE III.—*Tabular Summary of Wrought-iron Work in the Conway Bridge.*

One Roadway, length 424 feet.

	Top of the Tube.	Sides of the Tube.	Bottom of the Tube.	General Summary.
	Tons.	Tons.	Tons.	Tons.
Plates	239	201	242	682
Angle-iron and T-iron	115	146	59	320
Covers	15	21	78	113
Rivet-heads	23	24	17	64
Total	392	393	395	1180

TABLE III.—(*continued*).

	Length.	Weight.	Tons per Foot run.
	Feet.	Tons.	
Clear span between the supports	400	1112	2·78
One roadway complete	424	1180	2·78
Both lines complete	848	2360	5·56

Plates, 58 per cent; Angle-iron and T-iron, 27 per cent; Covers, 10 per cent; Rivet-heads, 5 per cent.

TABLE IV.—*Sectional Area and Depth of the Conway Bridge.*

Distance from extremity.	Top of the Tube.	Sides of the Tube.	Bottom of the Tube.	Total Sectional Area.	Extreme Depth.	
Feet.	Sq. inches.	Sq. inches.	Sq. inches.	Sq. inches.	Ft.	In.
0	478·55	276·25	372·90	1127·70	22	5
50	532·05	261·00	372·90	1165·95	23	4
100	565·81	241·00	460·58	1267·39	24	0
150	611·47	250·00	535·65	1397·04	24	10
Centre—200	645·30	257·0	535·65	1437·95	25	5

CHAPTER III.

THE CAST-IRON WORK AND SUPPORT OF THE TUBES THROUGH THE TOWERS.

THE small bearing surface on which the tubes repose, and more especially the limited space to which the attachment of the chains for raising them was necessarily confined, rendered some special precautions requisite at each extremity.

As regards the permanent bearing of the tube on the bed-plates in the towers, the strain is so completely a crushing strain, and the value of cast-iron in resisting crushing is so much greater than that of wrought-iron, that from motives of economy this material was naturally introduced under such circumstances; but with such studied precaution, that although 2000 tons of cast-iron have been used by Mr. Stephenson in the construction of the Britannia Bridge, with the exception of the hydraulic presses and a few small transverse beams across the top or bottom of the tube at the extremities, the whole of this immense mass of material has been introduced in such a manner as to be subjected only to a strain of compression.

The weight of cast-iron actually united with wrought-iron in the tubes is 1015 tons; it is employed solely in the passage of the tubes through each tower, and at their bearings on the abutments, where it prevents the distortion or crushing of the wrought-iron from the weight of the tube itself, and affords a secure attachment for the chains employed in raising the tubes to their places.

There are two distinct descriptions of castings in use in the tubes, viz., a series of upright castings in the interior, riveted to the sides of the tubes, and connected by horizontal castings across the floor and across the top, the whole forming a complete frame within the tube; and, secondly, a series of castings lying in the bottom cells beneath the above, to stiffen the vertical directions of the cells, and prevent them from being crushed under the weight of the tubes, both kinds being used over the towers exclusively.

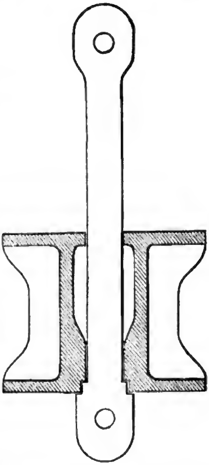
The frames first mentioned are strong cast-iron pillars, having a similar section to an ordinary H-girder. They are fixed upright against the side-plates, in the space between two of the angle-iron joints, and are strongly riveted to the plates throughout the whole length. The depth of these pillars is 14 inches, the front flange is 2¾ inch thick, and 10 inches broad. The back flange, which is perforated by the rivet-holes, is 2 inches in thickness and 15 inches in breadth; and the connecting web 2¼ inches; their height of course varies with the depth of the tube, those at the centre being 25 feet 10½ inches, while those at the extremities are only 19 feet; they are called Y-castings, and are represented under that name in Plate XXIII. The upper and lower sills are represented in the same plate as W and Z-castings respectively; they are very similar in section to the upright castings; they are attached to the tube and to the upright castings by 1¼ inch screw-bolts.

There are thirty-six of these frames in each line of tubes; their arrangement is shewn on the plan of the D-platform in Plate XX.; it will be there seen that there are three frames in each of the abutments, nine in the side-towers, and twelve in the centre tower; they are usually placed 4 feet asunder. Eight of these frames are, however, different from the others, and are called X-frames; they are the frames by which the tubes are lifted, and they differ in having deep notches, or recesses, cast in the front flange, which is 15 inches wide, for the reception of the ends of the lifting-beams, and in being attached to the sides by a greater number of rivets; they are represented in Plate XXIII. as X-castings. There are two of these lifting frames at each end of the large tubes, and also one Y-frame; they are built in the tubes previous to their being floated, and perform an important office in stiffening the ends while resting on the piers, as well as during the lifting. These three frames are inserted at the extreme ends of the tubes, and are only 2 feet apart; they are easily distinguished by this circumstance in Plate XX.

The lifting-frames are attached to each side of the tube by eighty-eight rivets, 1¼ inch in diameter, and the holes are carefully rimered previous to their insertion. The tube is raised almost entirely by these rivets, and as their combined sectional area is 432 inches, they have to resist a shearing strain of little more than two tons per square inch.

As the top and bottom cells do not possess much stiffness transversely, no dependence is placed on them in lifting, and the castings are only attached to them by screw-bolts; but the lower sills perform an important office in distributing the weight of the tube over the bed-plates, which would otherwise, on account of the flexure of the bottom, be supported wholly on the outer edges of the bed-plates, immediately under the sides.

Plate XIX. is a representation of the end of one of the large tubes immediately previous to its being floated, and will illustrate the use of these lifting-frames. The chains are attached to them through the intervention of three pairs of lifting-beams, which are fixed across the tubes, their ends fitting under the lugs or notches of the X-frames. It will be observed, that the centre pair of lifting-beams are somewhat smaller than the others; both kinds are figured in Plate XXIII. In section they resemble ordinary T-girders, with a one-sided flange only. The heads of the chains are slotted into two steps, as shewn in the accompanying sketch, and are tightly embraced between each pair of these girders, the bearing coming immediately under the vertical rib. The lifting-beams are firmly clasped to the chains by cast-iron clamps and screw-bolts, as shewn in the Plate. The contrivance of slotting two slips upon the heads of the chains, instead of one shoulder, was first used by Mr. Tierney Clark in the chains of the Pesth Suspension-bridge; it obviates their liability to break by a fracture commencing in the acute angle of the shoulder.



Thus two frames are brought into action at each end of the tube; and they can only fail by stripping the rivets which connect them to the sides, or by the shearing off of the lugs on the castings. To prevent them from springing asunder, a 4-inch wrought-iron bolt is cottered through the frames across the tube, as in the Plates.

Thus far all the strain comes upon cast-iron; but in accordance with Mr. Stephenson's design, that all tensile strains should be intrusted to wrought-iron, it will be observed, that the transverse beams are assisted by a pair of wrought-iron Λ-shaped straps, which pass over a stout wrought-iron saddle, upon the middle of the top pair of lifting-beams, and extend diagonally down through the floor into the outer cells, where they are secured by strong keys immediately under the base of the lifting-frames. In order that the lower lifting-beams may be assisted by them as well as the upper ones, cast-iron pillars are inserted between each pair of lifting-beams, and wedged up, so that any strain on the lower beams is at once transmitted to the upper pair of beams, and if of undue amount, is from thence conveyed down to the base of the lifting-frames by wrought-iron straps.

These straps have a sectional area of 64 square inches, and are used at each end of the tube; they are therefore sufficiently strong to raise the weight by themselves. In lifting the tubes, a very heavy strain, probably equal to half the entire weight, was imposed upon these straps by the hydraulic presses, before the lifting-beams were keyed up, it being certain that they would yield without injury to any over-violent treatment; while the first indication of undue strain upon the lifting-beams would have been given by their abrupt fracture.

As there was at all times a possibility of the weight becoming suddenly thrown on to the ends by the failure of the lifting machinery, hardwood blocks, which are not shewn in the drawing, were inserted between the bottom sills and the lower lifting-beams, to prevent the destruction of the bottom cells. This contingency actually occurred while lifting the tube, on the 17th of August, 1849, as narrated at page 691; and as the packing was at that time under the middle of the tube only, the entire weight came upon these blocks. They, however, became partially crushed by the blow, and the bottom became so much bulged upwards, that the three bottom sills were all broken, and had to be taken out and replaced. After this occurrence, cast-iron blocks were substituted, and four oak pillars, 18 inches square, were interposed between each of the lifting-beams, to assist the iron pillars in the event of the recurrence of such an accident. In this state the ends were entirely blocked up by an almost solid mass of iron and timber.

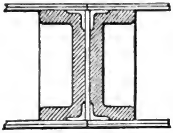
The Conway lifting machinery was designed before the great advantages in the use of wrought-iron for beams were fully appreciated. The whole of the apparatus except the chains was consequently of cast-iron. There were no wrought-iron straps, as at the Britannia, and no pillars between the lifting-beams; and there were only two sets of these lifting-beams at each end, instead of three, the middle pair shewn in Plate XIX. being used only at the Britannia.

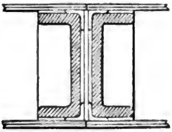
The tie-rods across the middle of the tube were also omitted; in other respects, the apparatus within the tube was precisely similar to that above described, and the identical lifting-beams were used at both places.

The same absence of wrought-iron prevailed at Conway in the machinery above the tube. The large wrought-iron girders figured in Plate XVI., which formed the foundation for the presses and their load, were made expressly for the Britannia; their place was supplied at Conway by cast-iron girders. (*See* Plate XLII.) They were assisted by a pair of smaller beams laid upon the top of them; they are both figured in position in Plate XLII., with the press resting upon them, and are marked A 1 and P.

The large cross-heads, the press-jackets, and the clam-beams, were also entirely of cast-iron; whereas at the Menai they were all strengthened by wrought-iron.

The other descriptions of castings used in the interior of the tubes—viz. those within the bottom cells—are called **G**-castings; they are seen *in situ* in Plate XIX., and their form and dimensions are given in Plate XXIII. They are used immediately under the **X** and **Y**-frames over the towers, and their principal office is to support the weight of the tube over the bed-plates, and prevent the cells from being crushed. They are inserted in the cells in pairs, placed back to back, enclosing the vertical plates between them, and are held in place by quarter-inch screw-bolts passing through all, as shewn in the elevation at Plate XIX. They are very accurately fitted or packed, to bear against the top and bottom of the





cells, and especially against the angle-iron connecting the vertical plates with the **D** and **E** platforms. In the Conway Tubes they were shaped out so as to fit the angle-irons, as shewn in the sketch. But their application was rendered much easier in the Britannia, by introducing narrow packing-strips of the same thickness as the flanges of the angle-iron, so as to give them a flush bearing, as in the accompanying figure. In addition to the resistance they offer to the crushing of the vertical plates, they perform another important office, by assisting the bottom of the tube to resist the enormous longitudinal compression induced by lowering the tubes after they have been connected together. With this object, they are carefully butted end to end against each other, and are extended entirely through the towers. Their usual length is eight feet; and there was one set of them in each end of the large tubes before they were floated; and the same at Conway. Referring again to Plate XIX., it may be observed, that there are no **G**-castings at the centre **V**-plates: they were omitted in consequence of the bed-plates not extending to the middle. It will also be seen that the outer ones are, for an obvious reason, much narrower than the others. Though they considerably contract the dimensions of the cells, sufficient space is still left between them for workmen to pass from end to end of the tube. There are no castings in the top cells; their general arrangement in the tubes is shewn in Plate XX. in the column of **V**-plates, where they will be seen to extend through the centre tower and side towers, and for a distance of 12 feet over the bed-plates in the abutments.

The only other attachments to the tube are the suspension-bolts, by which the tube is partly suspended where it passes through the towers. These bolts are 3 inches in diameter, and have been technically called "spade-bolts;" they are attached to the sides of the tube externally, by means of the flat spade-like portion of the bolt which is riveted to the side, as in Plates XIV. and XIX., their ends projecting above the top of the tube, and then passing through a series of transverse castings, marked H (Plate XVII.), which are not connected with the tube, but are supported at either end upon a beam (marked F X), which rests upon the masonry of the towers. These bolts are thrown into a state of tension by means of the large nuts at their extremities, which bear on the upper surface of the H-beams.

There are twenty-four of these bolts in the Britannia Tower, twenty in each side-tower, as shewn in Plate XIV., and six in the abutments, making altogether seventy-six bolts in one line of roadway. Their effective sectional area may be taken collectively at 370 square inches, and therefore with a strain of about 14 tons per inch they would be capable of supporting the whole weight of the tubes.

The Support of the Tubes in the Towers.

Each complete line, weighing 5187 tons, is partly suspended and partly supported, in such a manner, that although secure from any lateral motion, or sway upon its base, it is at liberty to expand and contract in the direction of its length without impediment.

The main spans, when constructed on the beach, were supported for some months upon a base occupying only 8 feet of their length at each end; they rested on a bed of hard wood on stone piers constructed for the purpose. The area of this bed at each end was, therefore, 120 square feet, and the weight supported on each bed 630 tons. But the weight was not equally dispersed over this bed, for although the bottom of the tube has considerable strength as a transverse beam, and is further assisted by the three lower sills of the frames at each end, in conjunction with the castings in the cells, yet this system is not rigid enough as a beam to exert much pressure on a horizontal bed of hard wood. The weight was therefore found, as was expected, to be supported more immediately by the sides, and indeed the packings under the middle of the tube were purposely left slack to prevent any damage to the bottom. When raised to their places these tubes were again supported on a bed of much less dimensions in the towers; but ultimately when the tubes were all united, the permanent bearing of the tube was much increased in area.

A single line is supported in the following manner:—First, by four fixed bed-plates in the Britannia Tower, as shewn in Plate XVII., on which the tube rests, and by the twenty-four wrought-iron suspension-bolts, also secured to fixed castings in the masonry, from which it is partly suspended.

Secondly, in each land-tower the bottom rests on four similar bed-plates, as in Plate XVIII., and is suspended by twenty-two similar bolts; the bed-plates and bolts are, however, in this case not fixed, the former resting on cast-iron rollers, and the latter on gun-metal balls, allowing the whole supporting system to move longitudinally with the tube.

Thirdly, over the abutments each extremity of the tube is supported on two similar movable bed-plates on rollers, and suspended by six similar suspension-bolts attached to movable castings. In this manner the whole line is entirely supported; it rests, therefore, jointly upon the 264 cast-iron rollers and 132 gun-metal balls, and the fixed bed-plates in the Britannia Tower, its support being everywhere entirely vertical.

In the Britannia Tower the beam rests on four cast-iron bed-plates; they are 12 feet long and 6 feet broad, and are placed upon a bed of creosoted deal 3½ inches thick, laid upon the cast-iron girders marked A 2 in Plate XVII., and on the masonry of the tower levelled for that purpose.

The bed-plates are 3½ inches thick, and on the upper surface another layer of creosoted deal 3½ inches thick was prepared. On the top of this deal a thick layer of putty of red and white lead was spread.

The wrought-iron bottom of the tube being perfectly flush, that is, without any projecting rivets, was lowered gently by means of the presses, the putty under this pressure being forced between the crevices of the plates and the planks, and rendering the whole impervious to water or air.

After the tube was thus lowered the bed-plates were relieved of some of their weight, and the tube itself partly suspended in the following manner:—Cast-iron brackets marked F F in Plates XVII. and XIX*. were built in the masonry of the tower to prevent the possibility of breaking off the angle of the masonry under the strain; the longitudinal beams F X rest on the extremities of these brackets. The cast-iron girders H H bear upon the F X beams at each extremity, without being in contact with the top of the tube; the spade-bolts attached to each side of the tube are inserted through these H-beams, and by means of large nuts, with a powerful spanner, moved by block-tackle, the requisite degree of strain is put upon these bolts, tending to support the tube, and dependent on the elasticity of the material in the tube and in the castings. It is calculated that in this manner about one-third the weight of the tube is permanently supported, with this important advantage, that, being secured both at the top and the bottom, any lateral sway from wind is avoided.*

The details of these castings will be found in Plate XXIII., and are referred to by means of the same letters. The F X girder is not shewn, but is similar in section to the **F**-girders.

The bearing in the side-towers and abutments differs in no respect from the bearing at the centre, except that the upper bed-plate and the beam F X are here made movable. Creosoted timber is first laid on the masonry as before; a bed-plate of cast-iron is next placed on this timber; four sets of cast-iron rollers, secured in place by means of wrought-iron frames, as shewn in Plates XVIII. and XIX*., are arranged on these bed-plates; immediately above the rollers comes another bed-plate, on which is placed a similar layer of creosoted timber, with red and white lead putty as before, on to which the tube is lowered. These rollers are cast in chills and not turned; the axles at each end pass through the wrought-iron frame that surrounds them, and preserve them parallel and in place. There are twenty-two rollers on each bed-plate, and they are each 6 inches in diameter. They are shewn in Plate XIV. in connexion with the bed-plates, and with the cast-iron A 2 beams, as before described; but only two of these beams were used, although three were originally intended.

Another view of these rollers is shewn in Plate XIX*., and it will be observed that the bed-plate on the Britannia side of the tower is thicker and heavier than on the other side; it is also cast hollow.

The top system of support will be understood by reference to Plates XVII. and XIX*. The beam marked F X is a fixture in the Britannia Tower, resting on the brackets F F; but in the land-towers this beam is at liberty to move longitudinally, by resting on a row of gun-metal balls placed beneath it for this purpose. The bottom of the beam is channelled, as shewn in Plate XXIII., E-girder, and in the accompanying sketch. The balls are supported in a lower channelled beam, as in the right-hand figure, E-girder, and are retained equidistant by axles passing through them, connecting them with a wrought-iron frame, which moves with them. They are 6 inches in diameter, and correspond in position with the rollers beneath. There are thus four systems of these framed spheres or balls in each land-tower, and two systems in the abutments.

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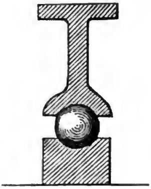
* These screw-bolts afford sufficient purchase for raising the small tubes; and, indeed, in finally tightening the nuts, one extremity was unintentionally raised from its bed, the weight being at that time almost entirely absorbed in counterbalancing the large tubes.



This kind of suspension not only relieves the weight from the bed-plates beneath the tube, but also prevents any lateral sway from the effect of wind, though it offers no impediment to longitudinal motion.

The support of the Conway Tube is precisely similar to that of the Britannia. At the Conway extremity of the bridge the tubes rest on fixed bed-plates, and are partly suspended from fixed girders across the top, so that the whole motion from expansion and contraction takes place only at the Chester extremity of the tubes, where bed-plates and rollers are employed exactly similar to those on the abutments of the Britannia Bridge; and the top is in a precisely similar manner suspended from girders resting on a longitudinal row of gun-metal balls, supported by a channelled beam resting on the masonry.

The timber placed beneath and above the bed-plates has been found perfectly efficient in preserving them from fracture under any unequal strain, and the rollers and balls are found to move freely during changes of temperature.

A table of the weights of some of the principal castings is appended:—

	Tons	cwt.	qrs.
The small presses used both at Conway and the Britannia (each)	11	0	0
Cross-head for the double press, with cast-iron tension-rods	15	4	2
Jackets for the small presses (each)	5	19	3
Rams for the small presses	2	15	0
The large single press	14	8	2
The cross-head complete	13	7	2
The jacket	8	3	0
The ram	3	13	1
Wrought-iron A 1 beams from which the tube was suspended while lifting (each)	11	16	1
Cast-iron A 1 beams used at Conway	12	1	0
A 2 beams (Plate XXIII.)	11	3	0
A 3 beams (Plate XXIII.)	6	14	2
Lifting-frames within the tube (average)	10	10	0
Lifting-chains (average per link, or length of 6 feet)	0	17	1

TABLE I.

Tabular Summary of Cast-iron Work in the Britannia Bridge.

	Carnarvon Abutment.			Carnarvon Tower.			Britannia Tower.			Anglesey Tower.			Anglesey Abutment.			Total.		
	Tons	cwt.	qrs.	Tons	cwt.	qrs.	Tons	cwt.	qrs.	Tons	cwt.	qrs.	Tons	cwt.	qrs.	Tons	cwt.	qrs.
Fixed beams and wall-boxes	39	0	2	212	2	0	394	12	1	212	2	0	71	0	2	928	17	1
Bed-plates, and rollers, and suspending-beams	63	16	3	169	16	3	84	0	2	169	16	3	63	16	3	551	7	2
Castings in the interior of the tube	35	18	3	128	9	1	178	12	3	128	9	1	35	18	3	507	8	3
Summary..........	138	16	0	510	8	0	657	5	2	510	8	0	170	16	0	1987	13	2

TABLE II.

Summary of Cast-iron Work in the Conway Bridge.

	Tons.
Castings fixed in the tubes	201
Bed-plates, rollers, &c.	108
Fixed in the masonry	325
Total	635

CHAPTER IV.

DESCRIPTION OF THE HYDRAULIC PRESSES.

THE real advantage derived from the use of this extremely elegant and simple machine, as employed in raising the tubes from the shelf at the base of the towers to their permanent position is sometimes misunderstood, under the vague impression that it "gains power" in some manner by an application of properties peculiar to liquids. The fact of its being only a more convenient machine than many others for accumulating intense action through a small space by a corresponding consumption of feeble action through a larger space, has been sometimes lost sight of. Indeed no machine gains power in the sense in which this expression is often understood. A pressure equivalent to 1 lb. continued through a given space overcomes a resistance of 1 lb. through the same space, and no combination of machinery can cause this power to overcome a greater resistance through the same space, or the same resistance through a greater space. We may, however, by the intervention of machinery increase the resistance overcome to any required extent by a corresponding sacrifice of the amount of motion or space moved through, precisely in the same manner as, with two arithmetical factors, we may increase either of them to any extent, provided we reduce the other in the same proportion, without in any way affecting the value of the product. In order that we may therefore be said to gain power, the term "power" must signify only the resistance overcome without reference to the space through which the effort is continued.

A pressure of 1 lb. through a space of 1 inch at the end of a lever, with equal arms, will raise 1 lb. through the same space of 1 inch at the opposite extremity, and no contrivance will enable it to do more.

If one arm of the lever became twice as long as the other, then, indeed, 1 lb. at the end of the longer arm would raise 2 lbs. at the end of the shorter arm; but if the 1 lb. move through a space of 1 inch, the 2 lbs. will be raised only half an inch.

If it were required that 1 lb. should raise the tube, or 2000 tons, then one arm of the lever must be 448,000 times as long as the other; but if the 1 lb. move through a space of 1 inch the tube will be only lifted $\frac{1}{448000}$th part of an inch; and, in order to raise the tube 100 feet, the pressure of 1 lb. must be continued through a space of 83,522 miles; and conversely, a pressure of 2000 tons, through a space of 100 feet, would raise 1 lb. 83,522 miles. Thus, the descent of a clock-weight through a space of 6 feet overcomes the friction of the machine and moves the extremity of an ordinary seconds-hand through a space of 2 miles in a week, and the descent of the tube to the water would maintain the going of an ordinary clock for 240,000 years.

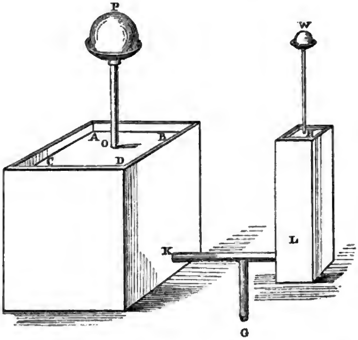
Whatever machine we employ, whether it be a lever, a screw, a train of wheelwork, block-tackle, or a wedge, the same equality still maintains between the cause and effect, or between the product of the space moved through and the pressure exerted on the one hand, and the product of the space moved through and the resistance overcome on the other. In considering the mechanical action of any machine, with this general law once established, we have no longer any occasion to examine the peculiar arrangement or mode of action of the machine itself, but simply to consider the relation between the motion or exertion at one extreme and the simultaneous motion and exertion at the other.

Thus, if we see the printer move the lever of his press through 10 inches, while the press descends only $\frac{1}{10}$th of an inch, or if we see the boiler-maker turn the handle of his punching-press through 10 feet, while the punch descends $\frac{1}{10}$th of a foot, or the sailor haul in 10 fathom of rope, while his topmast ascends only $\frac{1}{10}$th of a fathom, then, without troubling ourselves about the nature of the compound levers of the printing-press, or the eccentric of the punching-machine, or the arrangements of the sailor's block-tackle, we conclude at once, in all these cases (omitting friction), that the resistance overcome is precisely equal to 100 times the power applied, and this will be the case whatever be the nature of the mechanism of each machine. In this respect the hydraulic press differs from no other machine.

The moving power is the pressure of the steam on the piston of the steam-engine, and when this piston is pressed forward through a space of one stroke, or 16 inches, we observe the cross-head to ascend through a space of only $\frac{7}{100}$ths of an inch; a pressure of 1 lb., therefore, on the steam-piston, through any space, is represented in the cross-head by a simultaneous pressure of about 2 cwt. through a proportionately less space. Consequently, a continued pressure of $\frac{9}{10}$ths of a ton on the steam-piston will be sufficient to raise 2000 tons, which is the weight of the tube. Any other machine in which the first and last motions bear the same ratio to each other would answer the purpose, the hydraulic press having only this advantage, that the required increase of effect is obtained with less resistance from friction in this machinery than by any other contrivance.

The weight to be raised at the Britannia Bridge by a single press was 1144 tons. The elegant machine by which this was accomplished is as remarkable for its simplicity as for its efficiency.

Let A B C D represent a box 12 inches square, and let the square lid A B C D be so fitted in the box that it will move up and down in the inside without friction, and let it be supposed to fit so tightly that nothing can escape round its sides. Let H L be a similar box, of the same construction, the lid H being only 1 inch square. Suppose, further, the two boxes to be closed at the bottom, and to communicate with each other by a pipe K, of any size.



At the centre of each lid let a pillar O P, H W support a scale P, W on the top.

Let a weight of 1 lb. be placed on the scale W, and while the lid A B C D is temporarily fixed let atmospheric air be forced into the two cylinders through the pipe K G, until the weight of 1 lb. on W is just lifted by the pressure.

Under these circumstances the internal pressure of the compressed air will be just equivalent to 1 lb. on 1 square inch of surface. It will, therefore, exert a pressure of 1 lb. on each square inch of surface beneath the large lid A B C D;

and since the lid contains 144 square inches of surface, it is evident that the weight that will be required to be placed on the scale P to keep this lid from rising will be exactly 144 lbs. Thus 1 lb. at W balances 144 lbs. at P, in the same way that 1 lb. at one extremity of a lever 144 inches long would balance 144 lbs. on the other arm when it is only 1 inch long.

Let the pipe G be now closed. It is then evident that the slightest addition to the weight W would cause the lid H to descend, and the internal pressure being thereby increased, the lid A D, with its weight P, will be lifted; thus 1 lb. will be made to lift 144 lbs. through any space that may be required. But it will be observed, as in the case of the lever, that the descent of the weight of 1 lb. through a space of 1 inch will raise the weight of 144 lbs. through a space of only $\frac{1}{144}$th part of an inch, for the addition of 1 cubic inch of air of similar density to that already existing in the large box will only occupy a space of 144 in area by $\frac{1}{144}$th part of an inch in depth, which is, therefore, the space through which the large lid will rise to restore the equilibrium.

Such a machine would be an air-press; it would, however, be practically impossible to construct such a machine, because under any great pressure an air-tight joint could not be made with sufficient accuracy.

Now, all fluids thus compressed possess precisely the same properties as common air in exerting a corresponding pressure in every direction in which their motion is resisted. Thus, the boxes may be filled with oil, or water, or treacle, and still 1 lb. on the small piston will raise 144 lbs. on the large one, through a proportionately less space.

When water is thus employed the machine is called a hydraulic press. Oil is sometimes used, but water, as being more economical, is generally preferred.

This property of fluids has been known from time immemorial, but the same difficulty was always experienced in making the lid or piston water-tight as we should now experience in making it air-tight: an elegant contrivance for that purpose was devised by Bramah about fifty-four years ago, since which time this machine has come into general use, and has been called Bramah's Press.

Instead of the large square box, as in the figure above, cylinders of cast-iron, of great strength, to resist the pressure, are usually employed. A brass force-pump takes the place of the small box, by which a valve in the pipe K is forced open on the descent of the piston W, and on the withdrawal of the piston the closing of this valve prevents the escape of the water. The pressure is thus permanently maintained until another pump full is forced into the large cylinder.

Bramah's invention consisted simply in applying a packing for these moving pistons, which is perfectly water-tight under any pressure. This elegant invention rendered applicable a principle which was hitherto useless. The ordinary packing around the piston-rod in a steam-engine, for instance, consists of a soft material, such as hemp, which is forced mechanically into closer contact with the moving rod in proportion to the increase of the internal pressure. Under such a pressure as is usual with the hydraulic press the packing would require to be compressed around the moving ram with a force that would considerably interfere with its motion from the amount of friction.

The packing devised by Bramah is perfectly tight under all strain, independent of any lateral pressure against the ram, except that caused by the attempt of the fluid to escape, and by a species of self-adjustment the joint becomes closer sealed in proportion to the increase of pressure.

Figure 1 will explain the ordinary packing applied to force-pumps, steam-cylinders, &c. A A is the gland by which the hemp packing, H H, is forced into contact with the piston by means of the screws, S S. Fig. 2 represents the packing round the ram of the hydraulic press. The curved leather collar, L L, is kept in close contact, both with the ram and the cylinder, by the pressure of the water in the inside of the curve, and it is evident that the closeness of the joint is proportional to the amount of pressure.

Fig. 1.

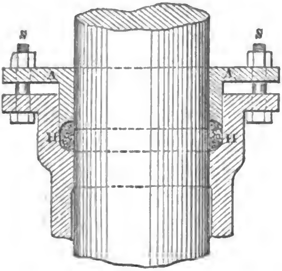
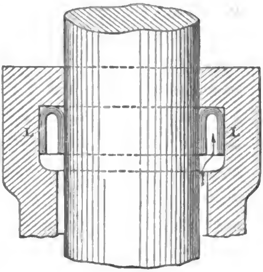


Fig. 2.



Complete details of the hydraulic press will be found in Plates XXVI., XXVII., XXVIII., and XLII. The single press used at Conway is represented in Plate XLII. The internal diameter of the press is 20 inches, the diameter of the ram is 18 inches, the external diameter of the press is 3 feet 1½ inch, so that the thickness of the metal is 8¾ inches. The water is forced into the cylinder through the aperture T near the top of the cylinder, the wrought-iron supply-pipe being nearly ½ an inch in diameter, and a full ¼ inch in thickness. The press is placed in a cast-iron jacket marked J, and thus rests on the beams marked P A', which are supported in the masonry of the piers.

The large girders marked A' weigh 12 tons each. The girder marked P is added for additional strength. An ½-inch deal plank was placed between the girders to equalise the pressure; a thin deal plank was also placed beneath the extremities on the masonry; but lead was subsequently substituted, and found more effectual. The jacket J was similarly bedded on a sheet of lead. The ram was cast hollow, as shewn in the Plate, and was turned to bed truly beneath the cross-head H. The ram was guided vertically by two wrought-iron 6-inch guide-rods, fitted in a socket at the top of the press, and keyed above into a cast-iron girder built in the masonry. The arrangement of the clamping apparatus for the chains will be understood from the Plate.

There are two sets of clams; the one placed on the cross-head, and rising with it, was immediately used for lifting the chain and tube; the under set is fixed on the cast-iron girders which support the press, and is used for securing the chain at the end of each lift while the press is lowered and the upper set of links removed. They are in all respects similar to each other. The wrought-iron clamping-cheeks are slotted to fit closely beneath the slotted shoulder in the head of the link; they are withdrawn or closed by right and left-handed screws, on turning which the cheeks recede from each other or are drawn into close contact with the chain. To ensure a parallel action, the screws are moved simultaneously by a winch and gearing. They are thus easily worked by one man.

Thus, at each stroke of the press the tube was raised 6 feet, the time occupied in one lift being usually from 30 to 45 minutes.

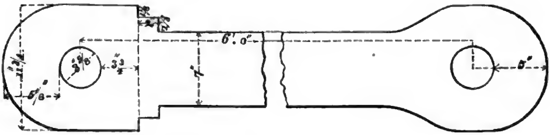
The lifting-chains were bored and slotted in sets with remarkable accuracy by Messrs. Howard and Ravenhill.

Each link consisted, alternately, of 8 and 9 plates, and was 6 feet long from centre to centre of the pin-holes. The sectional area of each link was nearly constant throughout the chain, the thickness of each of the 8 plates being 1¼ inches, and of the 9 plates $1\frac{1}{10}$ inches. The width of each plate was 7 inches.

The sectional area of each 8-plate link was thus 70 square inches, and the weight 16 cwt. 2 qrs. 16 lbs.

The sectional area of each 9-plate link was 69 square inches, and the weight 16 cwt. 2 qrs. 6 lbs.

The area of the four chains by which the tube was raised was thus 276 square inches. The greatest strain to which these chains were exposed was 8·3 tons per square inch. The pin and the bearing part of the pin-hole were visibly upset by this strain, but the extreme accuracy of the workmanship prevented all unequal strain, and the tube was suspended on these chains for several weeks.[*] Some of these links were tested with 15·3 tons per square inch, when the eye became sensibly upset and increased in thickness. The elongation of a length of 3 feet under this strain was ·225 inch, and the permanent extension ·175 inch. The following sketch contains the dimensions of the pin-hole, &c.



The steam-engine employed for working the pumps is represented in Plate XXVI.

The steam-cylinder C rests on an horizontal frame of cast-iron secured on wooden framing. The two pumps are worked by the direct action of the piston of the steam-cylinder, which passes through stuffing-boxes at each end of the cylinder. The whole of the arrangements are particularly simple and compact. The fly-wheels are moved by a cross-beam on the piston-rod. Two small fly-wheels were adopted instead of one larger wheel for compactness. The engine and boiler were placed in the lower level with the presses.

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[*] The pressure on the shoulders of these links was 10 tons per inch of area.

Minute detail of the force-pumps, which were made of brass, will be found in Plate XXVII., where the arrangement of the valves is shewn.

The weight raised at Conway was as follows:—

	Tons.
Wrought-iron work	1147
Cast-iron work	65
Lifting gear and chains	32
Timber	11
Miscellaneous	5
	1260

In addition to this weight, junction-pieces, weighing 35 tons each, were ultimately attached to each extremity of the tube, and were also raised by the press during the insertion of the bed-plates beneath them.

The steam-cylinder was 17 inches in diameter, or nearly 227 square inches in area, and the length of the stroke 16 inches. The piston of the force-pump was $1\frac{1}{16}$ inches in diameter, and the length of stroke similarly 16 inches.

Thus 36·124 cylindrical inches of water were delivered at each stroke of the engine, exclusive of waste.

Assuming the force on the plunger to be 3 tons per circular inch, or 3·386 tons on its whole area, then the force on the steam piston was 33·5 lbs. per square inch, the ratio of the area of the steam cylinder to that of the force-pump being as 256 : 1.

About $13\frac{1}{2}$ horse-power is required to lift 1000 tons 6 feet high in 30 minutes, *i. e.* at the rate of 2·4 inches per minute. The work done by the engine never exceeded this amount.

In order to lift the press 6 feet at this rate, the engine makes 1018 strokes, or nearly 34 strokes per minute.

The Britannia Presses.

The lifting apparatus used at Conway was designed for even a less weight than the Conway Tube, and was quite insufficient for lifting the Britannia Bridge, where the weight to be raised was as follows:

	Tons.
Wrought-iron work of the tube....	1587
Cast-iron work	79
Timber	41
Twelve lifting-beams	29
Pillars between the beams........	4
Wrought-iron straps, keys, &c. ..	12
Four chains	82
Three rams	7
Two cross-heads................	29
Suspended scaffold, &c.	44
Total	1914

The junction-piece passing through the land-towers, and weighing 175 tons, was ultimately attached to the extremity of the tube, and raised by the press in addition to the weight as above; this weight was, moreover, an overhanging weight; under these circumstances the distribution of the weight on the two sets of presses would be as follows:—

	Tons.
On the double press, Britannia Tower	921
On the single press, near the junction-piece..	1144
	2065

The above weight of 1914 tons was raised 100 feet. The rate at which it was raised was 6 feet per day. The time occupied in lifting 6 feet was usually about 45 minutes, and sometimes only 30 minutes; so that the whole rise might have been accomplished in one day if requisite.

The two small presses were employed for lifting one end of the tube; and a new press, with a 20-inch ram, was constructed for the other extremity, the double press being placed on the Britannia Tower.

In the new cross-heads that were now necessary a great addition of strength and security was obtained by the combined use of wrought and cast-iron.

These cross-heads are represented in Plates XXVII. and XXVIII. The part subjected to tensile strain in these cross-heads consists of four links of wrought-iron, with shoulders at each extremity fitted to the cast-iron. They were first fitted rather too short for insertion into the slots prepared for them. They were then expanded by heating them over a furnace. In this state they were dropped into their place, and by their contraction in cooling the extended portion of the cross-head was thrown into a state of initial compression; so that although the casting weighs upwards of 13 tons, it was visibly curved by this contraction, and only resumed its original form when supporting the weight of the tube.

Iron expands about $\frac{1}{10000}$th of its length by an increase of temperature of 15 degrees, and this extension is also equivalent to a tensile strain of one ton per square inch. An initial strain of 8 tons per square inch was put upon these links, consequently an increase of temperature of only 120 degrees was required for expanding them, and the space through which the links for the larger cross-head were thus expanded was $\frac{3}{20}$ths of an inch.

It will be seen that one side of the jacket which supports the press is also employed for supporting the lower clams; and as Mr. Stephenson wished that where possible every part of the lifting apparatus exposed to tension should be constructed of wrought-iron, large slabs, or cheeks, of this material were, after being heated, shrunk on the jackets; these cheeks thus formed wrought-iron beams, and in connexion with a second pair of similar wrought-iron beams, shewn in Plate XXVIII., formed a bed for the clams.

Lastly, the large cast-iron beams used at Conway for supporting the presses were here replaced by wrought-iron girders of peculiar construction. They are represented in Plate XVI., and consist of 6 vertical ribs of boiler-plate, $\frac{5}{16}$th inch thick, united by vertical covers. To preserve them in form the $2\frac{1}{8}$-inch spaces between the ribs are filled in with American elm planking, so that the vertical rib is a sandwich of elm and iron. The top and bottom flanges are each formed of 12 wrought-iron bars, extending the whole length of the beam; the top bars are 7 inches wide, and the bottom bars are 9 inches wide and $1\frac{1}{16}$ inches in thickness. The rivets pass through these bars, and also through the vertical plates forming the rib; the rivets are countersunk in the bars, and as each girder is made up of two pieces, connected side by side by the bolts shewn in the Plate, the length of the rivets is 5 inches, and they are $1\frac{1}{16}$ inches in diameter; the bolts are 15 inches long, and $1\frac{1}{8}$ inches diameter.

The weight of each of these girders is 11 tons 16 cwt. They are placed at such a distance apart that the body of the press is pressed between them. They are connected at each extremity by strong bolts 6 feet long and 3 inches diameter, which draw them into contact with cast-iron frames fitted between them.

In order to prevent the crushing of the thin vertical ribs at the points of support the wood packing ceases at 20 inches from each extremity, and cast-iron plates are inserted in its stead.

These beams may thus be considered as wrought-iron flanged beams, the sectional area of the upper flange being

103¼ square inches, and of the lower flange 132¾ square inches, the thickness of the vertical rib being 1⅞ inches.

The weight actually supported by one pair of beams was 945 tons; and when the tube was suspended from the clams in the double press this weight was suspended from two points, distant 3 feet 4 inches respectively from the centre of the beam, the whole length between the bearings being 17 feet 4 inches.

If we apply to these beams the reasoning employed at page 132, taking the depth at 3 feet 3 inches, *i.e.* to the centre of the flanges, we have their central strength as regards the crushing of the top—

$$W = \frac{39 \times 103{\cdot}25}{17{\cdot}33} 4 = 929 \text{ tons}$$

for each beam, or 1858 tons for one pair.

If we reduce the load to an equivalent central weight, as at page 225, and add the strength of the vertical rib to the strength obtained as above, it will be found that the strain from the weight of the tube was little more than 3 tons per square inch on the lower flange; and their flexure under this weight was only ⅛ inch.

The large single press, Plate XXVII., was of unusual dimensions. The internal diameter was 1 foot 10 inches, the diameter of the ram being 20 inches; the cylinder was 6 inches thick; its length externally was 9 feet 1½ inches, and the length of stroke 6 feet: on account of the great head of metal requisite in such castings, 21 tons of metal were run into the mould. The weight of the finished press was 13 tons 16 cwt. No less than four of these cylinders have been cast at the Bank Quay Foundry, at Warrington; they are, perhaps, the most powerful machines ever constructed.

The first cylinder was cast bottom upwards, and proved faulty, although every precaution was taken to feed the mould for many hours to supply the contraction in cooling. The defect was not discovered until the cylinder was turned and finished externally and internally, but on cutting off the waste head of metal at the bottom of the press a spongy hollow space was found in the centre of the metal, capable of containing upwards of a pint of water, and the cylinder was consequently rejected.

Another cylinder was cast in the usual manner, or in its natural position. The most solid metal was consequently at the bottom of the press, and the more porous metal at the top; but a head of nearly 7 tons weight was cut from the top of the press; the iron used was—

	Tons.
Blaenavon, No. 3, new pig, cold blast....	10
Pontypool, No. 3, ditto	3
Old Woolwich guns, probably charcoal iron	4
Glengarnock, a fluid iron, as a fuse	4
Total	21

The weight of the finished press was 13 tons 16 cwt., and 3 tons of Pontypool, No. 2 iron, cold blast, was used in feeding the mould during a period of six hours after the casting.

This press is represented on Plate XXVII., Cylinder No. 1, where a complete section is given. It was employed for raising the first tube, and failed by the separation of the bottom from the body of the press after raising the tube 24 feet, as described at page 691.

On first using this press it was found to be leaky at the top, the water, passing through the metal, rapidly filled the holes in which the guide-rods are inserted; the water also escaped through the metal of the ram, filling the interior, and running over the top from beneath the cross-head. The leakage of the cylinder was remedied by the addition of a second leather collar beneath the original one, by hammering the cylinder, and by forcing into the pores of the metal a thick gruel made of oatmeal and sal ammoniac. The filmy particles of the oatmeal were thus mechanically fixed in the pores by the corrosion produced by the sal ammoniac. The form of the bottom, which, instead of being conical, was nearly square, was doubtless the cause of failure with this press. The metal was found to be coarse-grained, the crystals at the middle of the fracture being much larger and coarser than near the surface; but the iron was perfectly sound.

The fracture did not occur where any great stress was produced by the internal pressure, but at the angle where the strain would be greatest from the contraction of a cooling mass of such a form. The internal pressure was about 3 tons per circular inch, and thus the tensile strain on the surface of fracture was about one ton per square inch.

Much discussion took place as to the best means of avoiding a recurrence of such an accident.

The strain on the cylinder of a press has been investigated by Barlow, and the practical rule for the requisite thickness, derived from his reasoning, is as follows:—

Having determined the pressure to which the press is to be subjected, the requisite thickness is determined from the formula—

$$\text{Thickness in inches} = \frac{\text{radius} \times 3}{6 - \text{pressure in tons per circular inch}}.$$

Thus for the 18-inch cylinder, with 3 tons per circular inch pressure, we have—

$$\text{Thickness} = \frac{9 \times 3}{6 - 3} = 9 \text{ inches.}$$

As a general rule, 3 tons per circular inch is the maximum strain at which presses are worked, and for this pressure the thickness of the cylinder should equal half the diameter of the press.

Beyond a certain thickness the addition of more metal to such a press would rather increase the danger than diminish it, for the iron becomes extremely defective in the centre of thick castings; and although with cylinders of prodigious thickness, the material does not all fail simultaneously, yet the inner layers first become separated, and, like a cracked plate of glass, the fracture gradually extends through the mass, whatever may be its dimensions. It is indeed probable that with less metal this press would not have failed. It was consequently determined not to increase the thickness, but to use all possible means, first, of obtaining close-grained metal; and secondly, of avoiding an angle of unequal contraction.

Cast-iron is rendered much closer by being run twice or three times through the furnace, and cast in plates on the floor; the metal is thus rendered extremely hard if used for small castings, but not when run in large masses; and Mr. Amos had found from experience that extremely close and strong castings for hydraulic presses may be insured by using only Blaenavon iron, No. 1, the metal being twice melted previous to being run into the mould. As this iron could not be rapidly procured, the following mixture was employed for the next cylinder:—

	Tons.
Blaenavon, No. 3, new pig	6
Do. old scrap..................	6
Pontypool, melted twice	3
Glengarnock ditto	4
Old Woolwich guns (charcoal)..........	3
Total	22

The modification which was made by Mr. Stephenson in the shape of the bottom will be seen in Plate XXVII., No. 2, where it will be perceived the square angle of the bottom is removed, and the bottom made conical. With this press the tubes were successfully raised; but to avoid delay in case of another accident, an additional cylinder, No. 3 on the Plate, was cast with a still deeper cone, the metal being—

Blaenavon, No. 1	10 tons,
Do. 2	10 tons,

the whole being twice melted, and run on the floor. These cylinders were cast with the bottom upwards, and the last has not yet been used; its weight is 15 tons.

In most cases hydraulic presses fail by splitting vertically down the centre, and on account of the incompressibility of water the fracture is generally quiet and gradual, without any explosive violence. In consequence of the frequency of such failures it has been supposed by some experienced makers that after being for a certain time exposed to so great a strain as 3 tons per circular inch, all cylinders will ultimately fail. There appear, however, after careful inquiry, no good grounds for this conclusion; the imperfection of the safety-valve renders it at all times doubtful what pressure is actually employed, and most cases of failure may be traced to some unusual pressure, though this could not be the case with the tube, the weight being freely suspended. An 18-inch press has been in constant use many years by Mr. Amos, the pressure being always 3 tons, and on some occasions 4 tons per circular inch. In some extensive works at Dover, where large hydraulic presses are used for drawing oil, five double and two single presses have been long in use; the pressure is constantly upwards of 3 tons; three cylinders have failed, and were all found to be defective castings, and one double press has been up 102,000 times.

Wrought-iron would, doubtless, give perfect security; but the construction of such large cylinders would be next to impracticable. Brass presses are sometimes used, and the ram is sometimes successfully lined with brass to lessen the wear.

The area of the large press for the Britannia Bridge is 314·16 square inches, and the capacity with a 6-feet stroke 22169·5 cubic inches. The quantity of water employed for a 6-feet lift is therefore 81·57 gallons = 815·7 lbs.

The pressure at 3 tons per circular inch = 3·819 tons per square inch, which would raise a column of water 5·41 miles in height; this pressure would, therefore, be sufficient to throw water over the highest mountains on the globe. The ratio of the area of the pump to that of the cylinder is as 1 : 354·3.

It is evident that, instead of a force-pump, a head of water may be conveniently employed for forcing water into the cylinder, and in this manner power may be stored up ready for use. The hydraulic press in this form is used for working cranes for unloading vessels, and other purposes where a more rapid motion is requisite.

In all cases where great pressure is required, the steady character of its action adds greatly to its utility ; among other uses it is extensively employed for compressing wool and hay, to facilitate packing, for drawing oil from seeds, for drawing lead and pewter pipes, for glazing paper, commonly called hot-pressing; for raising vessels in dry-docks, for raising turntables and swing-bridges on a central pivot to facilitate their circular motion, for pressing metals into moulds, and in a portable form a small press forms a very convenient substitute for the screw-jack, and has been extensively employed in moving heavy weights during the construction of the bridges.

SECTION VII.

THE CONSTRUCTION AND ERECTION OF THE BRIDGES.

CHAPTER I.

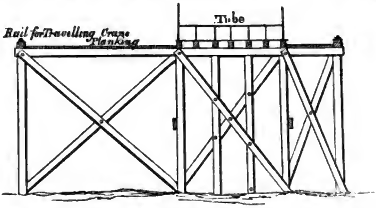
THE CONWAY BRIDGE.

Construction and Erection of the First Tube.

THE masonry which had been commenced in May 1846 was already in an advanced state when Mr. Evans' tender for the tubes was accepted in the month of October. Immediately after this period, a convenient site was selected, as shewn in plan, Plate XXXIV., and the platforms were commenced. They were prepared for the construction of a single tube, whereas, at the Britannia Bridge, the platform was designed as a recipient for completed portions of the work as it came from the makers.

The platform at Conway was 420 feet long and 40 feet broad. The beach beneath was partly composed of shale, and partly of alluvial deposit, wholly dry at low-water, but covered about 8 feet deep at high spring-tides. The piles were sunk slightly into the shale and dug into the deposit. The bays, as in the following sketch, were about 12 feet apart.

The tube was supported on longitudinal sleepers, corresponding with the cells in the bottom of the tube, so that the longitudinal joints were accessible for riveting. Considerable difficulty was experienced in keeping the platform true as the weight came upon it, and much additional strength was ultimately found requisite. Additional struts were inserted supported on sills bearing on the shale, and the platform eventually became a confused forest of small timber. The rail shewn in the sketch carried two travelling-cranes over-riding the tube, which were used for putting it together. Workshops, also partly supported on piles, were erected alongside the platform. They contained a twenty-horse steam-engine, with shafting, for driving three punching and shearing machines, a vertical drill and lathe, a fan-blower for the rivet furnaces, and, during the construction of the second tube, a powerful punching machine, made at Mr. Evans' suggestion, by Mr. Roberts, of Manchester.



Square wooden tubing led away from the fan-blower, and supplied a blast for the furnaces and forges at all parts of the works. The level of the top of the platform was at 21 feet on the local tide-gauge.

A crane for unloading plates was placed at the north-west extremity of the platform, and a riveting-machine erected in front of the sheds. Mr. Evans used the machine patented by Messrs. Garforth, of Dukinfield, shewn in Plate XXXI.

The general process of construction was as follows:—

The plates were first partially sheared: this was found requisite, although it had been arranged with the iron-masters that the plates should be manufactured as close as possible to the given dimensions. To render them perfectly flat they were next subjected to a very noisy process of hammering on massive cast-iron bed-plates, technically called "the stretching beds;" and although these cast-iron plates were 6 inches thick, this constant hammering on one surface speedily rendered them extremely convex, bending them more than an inch. The beds were then reversed, and repeated hammering on the other surface brought them flat again in time, and curved them in the contrary direction. This process was several times repeated. The bed-plates for the Conway Bridge were delivered extremely convex from the foundry, and they were straightened by a similar process, viz. by constant hammering on the concave side; and though they are 3½ inches thick, they were in this manner easily straightened.

The wrought-iron plates, being thus stretched, were next marked for punching: for this purpose a wooden or iron template was prepared, in which the requisite holes were bored. The template being placed on the plate, the position for the rivet-holes was marked with a stick dipped in whiting.

The angle-iron and the T-iron were straightened in a similar manner by hammering; the ends being forged square to insure good butt-joints; and they were marked in a similar manner either by a template for the purpose, or by being temporarily placed in their permanent position and marked through the holes to which they were to be riveted.

The bended T-iron for the knees was forged into a curved shape upon a cast-iron pattern or block, and the angle-iron was cranked for passing over the covers in a similar manner by the smiths at the forge.

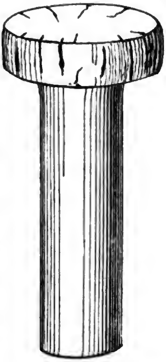
The operation of punching was performed by the ordinary punching-press worked by a crank with a fly-wheel, the plates being moved by workmen to bring the marked places beneath the punch, which was forced through the cold plate by the machine, the burrs dropping into the hollow die or bolster beneath. In some cases the punching-machines pierced two holes simultaneously, and even three holes, through a three-quarter plate, the dies being a little in advance of each other, and not experiencing the full resistance of the plate simultaneously. The pressure required for punching an inch hole through a three-quarter plate is about 46 tons. The bars are considerably heated by the compression and friction. The punches have flat ends, which soon become rounded and blunt by use; the bolsters also become rounded, and then make ragged, bad work. A good punch will last about three days and make about 8500 holes, and one machine with a double punch will make about 5670 holes in a day. With lighter work, such as gasometer work, the machine worked by hand will punch 60 holes a minute. The jar and blow frequently break the cast-iron lever of the machine. The substitution of wrought-iron for cast-iron for all the moving parts in these machines was found to be a great improvement.

The iron thus prepared was taken to the platform and fitted together,—an operation technically called plating. The bars and plates were drawn and secured into their places by cotter-pins and bolts.

The plates were thus put together in large portions, preparatory to riveting, these single pieces weighing sometimes as much as 10 tons.

The process of uniting wrought-iron plates by rivets has been hitherto a peculiar feature of *boiler-work*, or iron ship-building, and had been little resorted to by the civil engineer until Mr. Stephenson proposed the construction of these bridges.

The rivets used in the bridges, when of average size, are made of $\frac{7}{8}$-inch iron rod, which is cut up in a cold state into lengths of about 4 inches by a pair of shears. These short lengths are then made red-hot on the floor of a kind of reverberatory furnace, and in this state are dropped into a mould, which in its simplest form is a block of cast-iron with a hole drilled in it about 1½ inch shorter than the length of the rod; the top of the rod protrudes therefore 1½ inch above the mould. By a few blows from a heavy hammer the projecting portion is flattened out into a head, and the rivet thus formed presents the appearance shewn in the accompanying sketch. This primitive contrivance is, however, superseded to a great extent by machinery, in which the head is not formed by blows, but by the steady pressure of a flat disc of iron, attached to a slide, and moved by a lever, or eccentric. Several heated rods are dropped into one mould, and are passed in rapid succession beneath the disc, which, descending to within a constant distance of the mould, flattens the heads quietly out to a uniform thickness. In ornamental work it is customary to substitute a cup-shaped tool in place of the flat disc, the heads then receive a more or less conical form, which, together with their uniform size, gives them a much neater appearance. The shears for cutting the iron rod are usually attached to the same machine.



Such is the rapidity of this process, that a man and boy can form from 300 to 450 rivets per hour with one of these machines.

The heads of the rivets frequently present a cracked appearance all round the edge, arising from the opening of the longitudinal fibre; this is not considered detrimental to their strength, but is rather regarded as characteristic of tough and fibrous iron.

In fixing the rivets, the men are assorted in gangs, or sets. A set of riveters consists of two *riveters*, one *holder-up*, and two boys. One of the boys is stationed at the furnace, which is either a portable forge with bellows, or a reverberatory furnace; he attends to the heating of the rivets, and casts them to the other boy, who picks them up with pincers and thrusts them red-hot into the hole destined for their reception, their points protruding about 1½ or 2 inches through the hole; the holder-up with his large hammer then maintains a pressure behind the rivet, while the two riveters assail it in front, striking alternately. They first give two or three blows round the rivet to bring the plates into close contact; they then drive as much of the rivet as possible back into the hole, so as to completely fill it, and lastly form the head by means of a cup-shaped tool called a *snap*, which is held on the rivet, and struck by the riveter to give the head a hemispherical form. The operation is performed very quickly, usually occupying about thirty seconds; or when everything is ready, many rivets in succession are closed at the rate of one per minute.

In ordinary boiler-work their hammers weigh from 2½ to 4 lbs.; but these were not sufficiently heavy to draw together the thick plates of which the tubes are constructed, and, moreover, the number of blows required by these light hammers occupied considerable time, and to some extent damaged the head of the rivet; and where the rivets were very long the metal was not wholly upset, so that the rivets were not in perfect contact throughout the plates. To remedy these disadvantages, the weight of the hammer was increased to 7 lbs. and of the holder-up from 30 to 60 lbs. with excellent effect, though some difficulty was experienced in inducing the riveters to change the tools to which they had been accustomed. This difficulty of overcoming the old prejudices of the workmen in a manufacture so entirely novel was present throughout the progress of the works. The holding-up hammer is made of cast-iron, and is furnished with a very thick and elastic handle about 10 feet long; the handle rests in a hook near the middle of its length, which the workman uses as a fulcrum to press the hammer against the rivet-head. In lighter work a short bar of iron held in the hands is employed, and is called a "dolly." In making boilers the holder-up is necessarily in the interior, and in riveting the top and bottom of the tubes he is also compelled to pass the whole day within the cells in complete darkness and in a confined and reclining posture, immediately beneath the deafening blows of the riveter. His solitude is shared by a little boy, who inserts the rivets into their places; they are passed to him through a hole made in one of the plates.

One furnace will supply several sets of riveters, and, not being portable, the rivets have frequently to be passed a considerable distance to the work. This is done by throwing them with a pair of pincers; and no spectacle has afforded so much amusement to spectators as the unerring precision with which boys only eleven or twelve years of age toss them to their destination. And when a large number of riveters were engaged on the top of the tubes by night, the constant succession of these red-hot meteors, ascending in graceful curves to a height of 30 or 40 feet, formed an interesting sight.

The rivets differ considerably in their weight, but would average about three-quarters of a pound each. Their length varies from $2\frac{1}{4}$ to 5 inches, besides the head, and their diameter from $\frac{7}{8}$ inch to $\frac{1}{16}$ inch; they are slightly tapered towards the point, and are $\frac{1}{16}$ inch smaller in diameter than the holes which receive them. The rivets usually pass through three thicknesses of metal, but occasionally through four, or even six. When the plates are not more than $1\frac{3}{4}$

inch thick an extra 1¼ inch is allowed for the head; for greater thicknesses 1½ inch, or even more, is necessary, in order to leave sufficient metal to thoroughly fill up the hole; when the holes in the different plates do not coincide they are rimered out with a half-round rimer.

The tubes of the Britannia Bridge were almost entirely riveted by hand; but in the Conway Tubes the steam-riveting machine was used wherever it was practicable. This machine is figured at Plate XXXI. It consists of a steam cylinder with a piston of very large diameter, but of only 9 inches stroke, working horizontally; the piston-rod passes through a stuffing-box in the end of this cylinder, and terminates with a cup-shaped die. A corresponding die is fixed opposite to it on the top of a pyramidal pillar of cast-iron. The work is temporarily tacked together by cotter-pins, and is brought to the machine in sections weighing several tons.

To facilitate the moving of such large masses of plates, Mr. Evans constructed a travelling-crane, moving on rails, on two stone walls for the purpose. To insure also a parallel motion in a vertical direction, the work to be riveted was suspended from two drums of equal diameter, connected by gearing, to insure their simultaneous motion.

The work could thus be guided with accuracy and facility in any direction in a plane between the dies. One man was sufficient for moving the travelling-crane and drums on the railway above. Two were employed in steadying and guiding the plates below, while one boy supplied the red-hot rivets from the portable forge, and another worked the machine. The hot rivets being inserted through the plates, are brought in succession between the two riveting dies; steam is then admitted behind the cylinder by a slide-valve, the piston is thrown violently forward, and partly by the blow, but chiefly by its actual pressure, the rivet is squeezed into form, both of the heads being hemispherical, by which it may generally be distinguished from hand-work. On withdrawing the handle the piston returns quietly to the back of the cylinder, and another rivet being brought between the dies the operation is repeated. Although the stroke of the piston is only from 1 to 9 inches, its diameter is 48 inches. The steam is used at a pressure of 40 lbs. per inch, and it consequently exerts a pressure of 32 tons upon the rivet. Machines of 36 inches diameter or less are used for lighter work.

The rapidity with which riveting was executed by this simple apparatus was very remarkable. The work, with a little care, was particularly sound, and Mr. Stephenson was anxious that it should be employed wherever it was practicable, especially where there were many layers of plates. In some experiments which were made, where the holes were purposely untrue, it was found, on planing down through the centre of the rivet, that the holes were completely filled up, forming a solid mass.

To insure close contact with many layers of plates, it was found advisable, on the introduction of a rivet, to strike the plates with the die round about the rivet, to bring them into close contact, previous to striking the rivet, and in some cases to continue the pressure, otherwise the rivet-iron is forced by the pressure into laminæ between the plates, which are permanently prevented from close contact, and the important advantage of friction caused by the cooling of the hot rivet is thus lost.

The principal advantage that this machine possesses over the lever riveting-machine is, that in the latter a fresh adjustment is required at every alteration of the thickness of the plates to be riveted, otherwise the machine is broken by the blow, which was frequently done purposely by workmen who objected to its introduction; whereas the thickness is quite unimportant with the steam cylinder, there being no definite amount of motion given to the die.

The plates were riveted in long strips by this machine, and united in their places by hand-riveting.

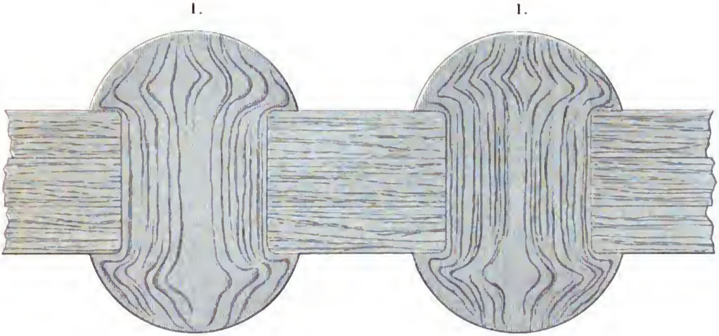
The men, who look with jealousy on any machinery which abridges their labour, were all advocates for hand-riveting; and so great was their influence in these matters, that although three riveting-machines were erected at very considerable expense at the Britannia Bridge, and one of them by the patentee himself, yet their use was not persisted in, and the whole of the Britannia Bridge is consequently hand-riveted.

Considerable discussion took place as to the superiority of either method, and the difference in the quality of the work is so trifling that the matter is still unsettled. Many rivets on both systems were cut out by opposing advocates, and plates riveted together were sectioned by the planing-machine through the centre of the rivets, to detect, if possible, any difference. It was imagined that the steady pressure of the machine more effectually *upset* the metal and filled up the holes without damaging the head by the blow. On the other hand, it is the practice of the strikers in hand-riveting to bring their work into close contact by occasional blows on the plate round about the rivet during the process of riveting; and by this means their work is brought and retained more thoroughly home, and greater friction ensured, while the rivet is prevented from oozing away in thin laminæ between the plate, which is sometimes the case with the machine.

The accompanying Plate represents a section through machine and hand-riveting, made at Mr. Stephenson's works at Newcastle. The grain of the iron is beautifully shewn by slightly corroding it, or *browning* it, as technically called by gun-makers, the work being first planed through the centre of the rivet, and polished.

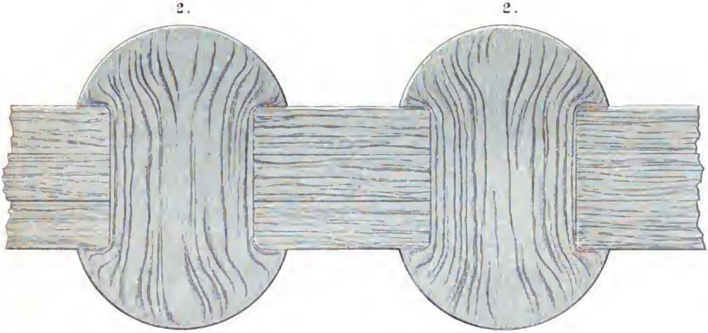
Some difficulty was experienced in properly combining the large portions of work as they came from the riveting

MACHINE & HAND RIVETING.



Nos 1.1. Shew the arrangement of the fibres in rivets made by machinery and rivetted by machinery.

Nos 2.2. Shew the arrangement of the fibres in rivets made by hand and rivetted by hand



Day & Son lithrs to the Queen

machine, and considerable force was sometimes requisite to draw them into place. The travelling-crane, over-riding the tube, was particularly convenient for transporting them.

In this manner the construction of the tube steadily progressed. It was commenced in March 1847; the lower part of it was completely riveted by the month of June, and the sides commenced; and it was found necessary to rimer many of the holes, as it was impossible to punch them with sufficient accuracy to ensure the perfect action of the rivet without this precaution. Great difficulty was experienced, also, in keeping the bottom in shape at the proper camber, which was fixed at 7 inches. The platform gave way under the weight of the plates, and interfered with the truth of the work. The piles, not being driven, sunk into the clay and rock, induced, no doubt, partly by the constant vibration from the hammers of the riveters; but, as the sides were not yet in their place, there was no difficulty in readjusting the bottom; which it was of great importance should be done before the sides were connected with it.

In spite, however, of all the care that was afterwards taken to remedy this defect, it was found impossible to preserve accurately the form that was desired, the timber itself being, to some extent, compressed as additional weight was added to the structure.

The progress made in the month of August will be seen in Mr. Stephenson's Report, dated 9th August, 1847:—

> "The masonry of the Conway is advancing as fast as it is expedient until the tube is ready, which is progressing very satisfactorily. In the commencement of this part of the work we experienced several delays, some arising out of the peculiarity of the work, others from the non-delivery of the large plates, which, being of an unusual size, required the construction of new machinery for their manufacture.
>
> "The whole is now advancing rapidly; the plans for moving

and raising the tubes are completed; the hydraulic presses and chains are in progress, and will be ready in time; two of the pontoons are complete, and the others in a forward state. One of the tubes on the platform at Conway is approaching completion; the whole of the bottom and a considerable part of the sides are finished; part of the top is in its place, a great portion of the remainder is finished and fitted, and in a few days a complete section of the middle portion of the tube will be entirely constructed.

"I am happy to say, that as we proceed in this part of the work it manifests all the strength and rigidity which was anticipated.

"Every exertion has been made to forward this bridge. Mr. Evans, the contractor, still expects to complete the tube by the middle of September; I do not, however, imagine that this will be possible; but, contingent on a sufficient supply of iron, I have no doubt it may be ready for the passage of trains in the month of November next."

Mr. Evans was now also proceeding with the construction of the pontoons, which Mr. Stephenson desired should be increased to six in number, instead of four, with decks for the purpose of strengthening them, and for convenience of those employed on board in working the capstans. They were constructed of deal, with the exception of some hard wood to resist compression from the weight of the tube; they are represented in Plate XXV., and consist of four longitudinal trussed timber frames, strengthened by wrought-iron ties to prevent the flexure of the ends, the weight resting on fifteen feet only at their centre. They were found to bend considerably under the weight in an experiment made with one of them, and were from time to time considerably strengthened. They were furnished with pumps, in case of leakage, and with brass valves at the bottom for admitting water for the purpose of sinking them when required. They were planked throughout with four-inch deal, spiked to the whole balks of which the framing was constructed. The weight resting immediately on the top sills of the frames was thus diffused over the whole boat, which was 98 feet long, 25 feet broad, and 8 feet deep. They were capable of carrying 460 tons each when completely submerged, or 57 tons per foot of displacement.

The sides were perpendicular, for the purpose of better combining them together, but the ends were sloped, to offer less resistance to the tide.

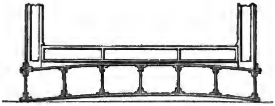
Each pontoon contains 5461 cubic feet of timber, and 6 tons 4 cwt. of iron. The cost of building them was about 1500*l.* each.

Several practical modifications were adopted in the course of the construction of the tube. The rivets in the bottom were increased from an inch to an inch and an eighth in diameter; double covers were added in the D and E platforms of the bottom of the tube, to obviate some objections to the method of riveting the plates longitudinally, and to supersede the complicated cranking of the angle-iron. For the union of the sides with the bottom, packing-strips were employed between the covers of the bottom plates. The top and bottom of the tube at the extremities were considerably increased in strength, as they had been tapered off in the design rather too consistent with theory. The sides were, moreover, strengthened, and the method of attaching the frames, and the castings in the cells, much improved. The fitting of these frames was found to be a tedious and expensive operation, from the want of chipping-pieces, and from the difficulty of inserting them so as to ensure close contact with the wrought-iron work, as this was done after the completion of the tube.

We have seen that the tube was constructed twelve inches shorter than the distance between the back of the recesses on either shore, which was 412 feet, and allowed only a bed of 6 feet at each end, but after the tube was raised, a further length of six feet was added at either end, and when these lengths were joined to the tube, the whole was then lowered, thus giving a permanent bearing of 12 feet in each tower. The construction of these end-pieces required some consideration. The arch in the tower was not wide enough to allow of their being put together on the shore, and then advanced to their place, and it was impossible to construct them in their place, the sides of the tube being within four inches of the masonry, a recess being left on each side, merely at the junction of the main tube with the junction-piece for riveting the sides.

It was, therefore, necessary to put these junction-pieces together on a platform in front of each tower, and move them bodily back into their place, in a proper position for uniting them. Each of them weighed about 50 tons, including the frames, and the castings in the cells.

Massive as the cast-iron frames necessarily were, they were weak as compared with the wrought-iron, which was immovable in every way. The bottom of the tube was built slightly curved upwards, as in the sketch below, and an attempt was made by means of screws to bring it straight. The cast-iron was deflected considerably, but the thin wrought-iron plates were immovable, possessing a transverse rigidity which no calculation could account for, except that through the intervention of the vertical plates a great length of the bottom of the tube was brought to its assistance.



The tube was nearly completed on its platform by the 8th of January, 1848, and its camber and shape were then determined. This was done by means of a 30-inch telescope made for the purpose. This telescope was attached to the extremity of the tube, on the outside, at a height of 2 feet 10$\frac{7}{16}$ inches, measured from the angle-iron which unites the sides with the bottom. The instrument was supported on Ys clamped to the side of the tube. It was carefully adjusted for collimation, and care was taken that the eye-piece moved parallel with the optical axis of the instrument in altering the focus, by special adjustments for that purpose, so that, on pointing the instrument to a fixed mark, either near at hand or distant, the mark was always bisected by the cross-wires, as the telescope was made to revolve in the Ys. A fixed mark corresponding in position with the telescope, was now attached at the other extremity of the tube, to which the telescope was accurately pointed, and in that position was clamped. The line of sight was thus nearly an horizontal line along the side of the tube; and as a permanent record of the original shape of the tube, small holes were drilled at intervals through the sides in the line of sight, by means of brackets fixed to the tube, but with vertical adjustments for that purpose, so that the optical axis of the instrument, and the top of all the brackets, and the fixed mark at the far end of the tube, were in a straight line; and, as the tube deflected, might be considered as an arc, the deflection at the centre being the versed sine. These holes will be found in the northern side of the northern tube, at the elevation mentioned, and will be a durable record of the original construction of the tube.

The bottom of the tube was not, however, in a straight line, but had a camber, or rise, of 6·49 inches in the centre, as measured from the outside angle-iron which connects the sides with the bottom. The curve of the bottom was, however, not regular, nor were the sides found to be perfectly true laterally.

Camber originally given to the Bottom of the Tubes in their construction on the Platforms.

FIRST TUBE OR UP-LINE.

Distance from the Conway end.	Camber.	Camber.	Distance from the Chester end.
Feet.	Inches.	Inches.	Feet.
0	0·	0·	0
50	3·91	3·59	50
100	5·89	4·85	100
150	7·31	6·04	150
200 (Centre)	6·49	6·49	200 (Centre)

On the 16th January, the operation of cutting away the platform was commenced, and occupied ten days of intense anxiety. The tube was supported at each end on piers of sandstone, built for the purpose, to within 20 inches below the bottom of the tube. They were 12 feet high, and 18 feet by 9 feet in plan at the top, with a slight batter. A layer of elm planking was placed on the pier 2½ inches thick; folding wedges of American elm 10 inches square at the larger end, and 7 by 10 at the smaller end, and 10 feet long, were then driven longitudinally between the bottom of the tube and the planking, the lower wedge only being driven, the upper one being accurately fitted to the bottom of the tube. These wedges were driven by a battering-ram. Previous to the driving of these wedges, some portion of the centre of the platform was removed for a space of 112 feet: the deflection was one inch and a quarter; the curve was, however, irregular. The great extra weight thrown on the remainder of the platform became very evident. After driving the wedges, and further removing the platform, as the tube descended and compressed the remainder of the timber, the difficulty of extracting it became greater and greater, and the timbers were cut out piecemeal. They became at length so compressed that great difficulty was experienced even in this operation. A hole drilled with an augur was immediately filled up by the pressure, so that it was impossible to bore to any depth; and great labour was required to splinter away the timber in small fragments.

The descent of the tube from its own weight was watched constantly with the greatest anxiety, as the operation proceeded at length night and day. The great problem was now being solved. Many had predicted a deflection of two or three feet, and a great number of high authorities had affirmed that the tube could not support its own weight, while others foretold the buckling of the top, distortion of the sides, and crushing of the extremities. Every phenomenon was therefore watched incessantly with intense interest, as the tube descended inch by inch. The crushing of the timber, moreover, at times, as it broke away under the strain, alarmed the men who were working beneath, and it was necessary to be continually present with them to keep them at their post. Mr. Stephenson, however, awaited the result with confidence, though not unmingled with deep anxiety, as the results of the operations from day to day were forwarded to him by the Author. By the 24th January, the bulk of the platform was removed, and the tube had descended at the centre 6½ inches. The pressure on the remaining props was estimated then at about 10 tons per foot, the longitudinal balks being nearly destroyed by the weight. Through some oversight in working in the dark, it was found that some of the central portions of the platform had not been cleared away, and the tube was resting, as it descended, on two piles, which were bent under the weight, but had considerably indented the bottom of the tube; on their removal, however, the plates resumed their shape.

Among other little incidents, considerable alarm was one night excited by a report that the tube had suddenly descended 7 inches, accompanied by considerable crushing of the timber. On proceeding to test this alarming phenomenon, by means of the deflection-instrument, it was more than confirmed, the instrument indicating a fall at the centre of nearly 9 inches. On more minute examination of the platform there were, however, no symptoms of such an extraordinary descent, and the instrument was again adjusted, and the alarming incident accounted for. The fixed mark to which the instrument was pointed at the further extremity of the tube was a square board, divided horizontally by a straight line, the upper half being painted white, and the lower half black; and the telescope was adjusted previous to every observation by making the horizontal wire in the eye-piece correspond with the division between the black and white portions of the board, on which a strong light was thrown in the night, by means of one of the crates of burning coal—technically called devils—by which the works were lit up at night. In hastily adjusting the instrument, the dark background of the prospect had been mistaken for the black division on the board, the night being very dark, and thus the instrument, instead of pointing to the centre of the board, was in reality cutting the upper line or edge of the board, and thus increasing the apparent deflection. All fears, however, were at an end on the 25th, when the whole of the platform was cleared away, and the tube took its own weight from end to end, with a deflection of $7\frac{7}{8}$ inches, being one-eighth less than had been calculated upon.

The first emotions on reflecting on this magnificent solution of the problem which had induced so much care and apprehension, were inexpressibly exciting; and though the novelty has ceased, no stranger can stand beneath this stupendous beam, tapered off, as it appears, by its vast perspective, without feelings of intense astonishment.

The Testing of the Tube.

The testing of the tube was now rapidly proceeded with. For this purpose rails were laid throughout the tube and platform. Ballast-waggons were then loaded with iron plates and drawn into the centre of the tube. The first 20 tons increased the deflection by one-eighth of an inch, and with 50 tons the deflection, as read by lamplight, was 9 inches. This weight was left in all night, and the deflection in the morning was only 8⅜ inches. This was attributed at the time to some error made in the reading; but this, and many other anomalies in the deflection, were afterwards fully accounted for by local changes of temperature. A gleam of sunshine on the top of the tube raised it on one occasion nearly an inch in half an hour with 200 tons at the centre, the top plates being expanded by increase of temperature, while the lower plates remained constant from radiation to the water immediately beneath them. In a similar manner the tube was drawn sidewise to the extent of an inch from the sun shining on one side, and returned immediately as clouds passed over the sun, being in fact a most delicate thermometer in constant motion, both laterally and vertically. This might be increased by the ends being fixed on the piers, which to some extent resisted longitudinal motion; they were, indeed, partially swayed to and fro by the lengthening of the tube.

On removing the 50 tons the tube had attained a permanent set of one-eighth of an inch; 90 tons were then placed over 90 feet at the centre, and the deflection on its removal was 8½ inches.

On the following day the deflection with 95 tons, which had been left in all night, was 9$\frac{5}{16}$ inches; 154 tons were then placed over 140 feet at the centre, the deflection being 9½ inches. Weights were thus added and removed, as in the following table. When 200 tons were left in all night, and increased to 300 on the following morning, the deflection was found to be $10\frac{13}{16}$ inches at the centre; and on the removal of this weight on the following day the deflection was $8\frac{13}{16}$ inches, decreasing gradually to $8\frac{10}{16}$ inches; and on the 4th of February, after the removal of the temporary rails inside, it was found to be only $8\frac{1}{4}$ inches (*see* the Table at page 660).

The Floating of the First Tube.

For some time previous to the testing of the tube, every preparation had been made for the floating of the tube. The plan of the operations had been most carefully considered and arranged by Mr. Stephenson, with the assistance of Mr. Evans.

The six pontoons were launched and tested. The necessary excavations beneath the tube, to make room for them, were completed, and they were brought into their places ready for lifting. As the tide rose and fell the valves at the bottom were left open, so that they were alternately filled and emptied without bearing against the tube. Timber struts were placed inside the tube, immediately over the pontoons bearing against the top, to prevent any distortion in the sides, or lower cells at a part of the tube where there was no provision against such a contingency.

The tides were, moreover, carefully observed, and on the 20th of February Mr. Stephenson took up his residence at Conway in order to superintend personally the necessary arrangements.

As the time approached his anxiety naturally increased, and to ensure that order and system so indispensable in the employment of so many hands—the bulk of them being sailors—and to assist, moreover, in the numerous nautical details involved in so important an operation, he now secured the valuable services of Captain Claxton, R.N., whose exertions were so eminently successful in bringing the *Great Britain* from Dundrum Bay. That gentleman accordingly took charge of the nautical detail, in which he was most ably assisted by an efficient body of seamen engaged at Liverpool for that purpose.

The arrangements for floating were, however, not sufficiently complete for the spring-tides of the 20th, and the operation was postponed to the 6th of March. Mr. Brunel remained with Mr. Stephenson during this interval, and kindly volunteered his valuable co-operation. The arrangements for floating were still further elaborated; fresh capstans were erected; the pontoons were tested beneath the tube, and the heavy mooring-chains were laid across the river. A strong gale of wind, which occurred on the 27th, afforded an opportunity of observing the horizontal motion of the tube, which amounted to about $\frac{2}{10}$ths of an inch, the vibrations occupying a little more than one second. The motions from change of temperature were also accurately observed by means of a fixed register, which was always in motion. A cold wind, with rain beating on the sunny side of the tube, caused, on one occasion, a motion of $\frac{13}{16}$ths of an inch in 20 minutes.

The changes from temperature on the 2d of March, between the morning and the afternoon, amounted to $1\frac{1}{2}$ inch horizontally, and 1 inch vertically.

As it was of the utmost importance that the length of the tube should accurately correspond with the distance between the abutments, and as the width of the river had only been obtained trigonometrically, this measurement was directly tested by two methods. First, a copper wire was suspended across the water from a given height on either shore, so that the centre of the catenary was just in contact with the surface of the water in a quiet tide; the wire was then placed in precisely similar circumstances on the shore, and adjusted to the same versed sine, and the horizontal distance directly measured.

And, secondly, rods of deal, threaded on a line for that purpose, were floated on the surface of the quiet water at the turn of the tide, being drawn into a perfectly straight line by means of the rope, which however caused no strain on the rods, and care being taken to ensure close contact at the end of each rod, the space between the towers was thus most accurately determined; and these measurements were all found to agree.

On the 3d of March all hands were mustered, and a rehearsal of the floating took place. During this rehearsal the Author in attempting to adjust a rope which was winding foul on one of the crabs in the pontoons worked by twenty-four men, incautiously placed his foot beneath a projection on the drum, by which the upper joint of the great toe was severed; and this accident necessarily confined him to his room, and vexatiously prevented his taking any active part in the floating, which was accomplished on the 6th.

A more minute description of the floating of the other tubes will therefore be given, in which the operation was precisely similar.

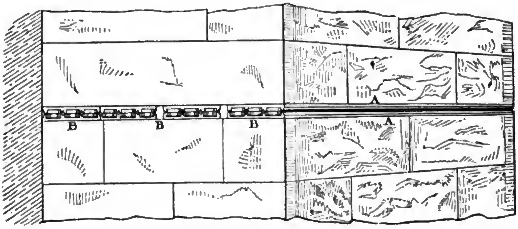
At a quarter past eleven on the 6th of March the tube, being lifted by the pontoons, began to move off, snapping the small ropes that kept it back; it glided quietly and majestically across the water in about twenty minutes. The Author was a spectator from a carriage on the Suspension-bridge. The town was full of distinguished visitors, and the weather was beautifully serene. The magnificence of the spectacle can scarcely be conceived. At eleven o'clock the deep and rapid Conway was an impassable gulf, and in less than half an hour it was spanned by an iron bridge twice as large as the centre arch of that of Southwark. The operation was as quiet as the effect was miraculous. As the mass crept along the heavy guide-chains, the beautiful valley of the Conway was imperceptibly veiled, and like a dissolving view, the hills disappeared, the estuary closed gradually, and the wide lake, with all its mountain scenery, was permanently obliterated from the magic scene. Unfortunately in approaching their ultimate position, one of the sets of pontoons, which had been slightly slued by the stream, fouled on the rock at the Conway end of the tube, which was thus prevented from being brought home; it was, however, blocked up on a temporary shelf that had fortunately been prepared in case of such an accident, and though not in its place, it was now secure, and crowds of people with music and cannon welcomed the new visitor into its berth, and climbed on to the top.

It was thus necessary to bring the pontoons again under the tube with the next tide to shift it into its place, and this apparently simple operation caused considerably more trouble and vexation, and almost as much expense, as the floating itself. It was found impossible to moor the pontoons in their position under the tube for the purpose of lifting it in so violent a tide, which rushes through the contracted opening with fearful velocity.

An attempt made on the 8th entirely failed. Another attempt on the 9th was equally unsuccessful. Some of the pontoons were moored in their place; but while adjusting others the first tore away from their moorings, and were strained and tilted by the tide to such an extent that they were in constant danger of being pulled to pieces or submerged in the tide, which even washed on to their decks. Some of them were carried out to sea by the ebb and stranded on the sand-banks in the bay. Several serious accidents occurred during these operations, and, after another failure on the 10th, Mr. Stephenson quite despaired of the possibility of effecting his object. On the 11th, however, after strenuous exertions, the pontoons were at length secured beneath the tube, which was again lifted by the rising tide, and moved the remaining few inches into its place.

In the meantime the presses and the raising machinery were fitted in the towers above. The corbelling of the recess, under which the tube had entered, was completed.

In order to secure a bearing between the old work and the new masonry built in beneath the corbels, cast-iron plates, B B B, as in the following sketch, were inserted between the courses of the stone-work; folding wedges were then driven between the plates, with sufficient force even to raise the whole of the upper masonry to the extent of three-fourths of an inch, slightly upsetting many of the upper joints. A secure bearing was thus ensured for the beams which carry the presses.



It was not until Saturday, the 8th of April, that the arrangements were completed, when the tube was raised 8 feet, under the directions of the Author, assisted by Mr. Amos. The rate of lifting was about 2 inches per minute. One 6-foot stroke occupied about 34 minutes, the engine making about 60 strokes a minute. A phenomenon occurred which created some alarm. The lifts occurring at equal successive intervals at each end of the tube threw the whole length into considerable vibrations, which became synchronous with the strokes of the engine, and increased to such an extent as to become unpleasant to parties standing on the tube. The cause was, however, soon discovered, and the effect obviated by occasionally stopping the presses, or working them at different and varying speeds, so as to break up the undulations.

On the 10th the tube was again raised 6 feet, care being taken to insert timber packings beneath. On the 11th the raising was completed, and the tube suspended from the clams attached to the presses 3 feet above its permanent level, for the purpose of joining on the end-pieces inserted in the towers, and arranging the bed-plates beneath it.

At this elevation there was some slight tendency in the press on the Chester side to tilt, the cast-iron beam to which the guide-rods were attached not being firmly secured in the masonry, and the cross-head not rising quite fair, ploughed away some of the iron from the guide-rods.

On the 16th, after working night and day during the interval, the tube was finally lowered into its permanent bed. The rails were laid through it, and, on the 18th, Mr. Stephenson passed through with the first locomotive.

It was immediately afterwards tested by the Government inspector, Capt. Simmons, and opened for railway traffic on the 1st of May; and on the 17th a public dinner was given to Mr. Stephenson by the inhabitants of Conway, on which occasion some interesting remarks were made by him, which are so closely connected with the history of the undertaking that they are here inserted, as reported by a local paper:—

"I believe it will be expected of me—indeed I should feel it improper if I were to omit on this occasion detailing very succinctly a few facts with reference to the rise and progress of the idea which led to the construction of tubular bridges, because, in doing so, it will not only afford me an opportunity of explaining to you precisely what the origin was, but it will also give me the opportunity of expressing my obligation to those who have so largely aided me in bringing about the result which we are met to commemorate. It is now upwards of six, or about seven years, since I entertained the idea of constructing bridges with wrought-iron plates riveted together. I was called upon—in a smaller case, I admit, but not a very simple one—to construct a bridge authorised by Act of Parliament, but with such limitations, that it became a matter of extreme difficulty. All the ordinary kinds of bridges were discussed, and I eventually hit upon the notion, and the designs were completed, *for a thin tubular bridge*, although not precisely the same as the present, yet *in principle precisely the same*. That was effectually completed, and answers its purpose, and may be now seen on the Northern and Eastern Railway. From that time, however, to the period of commencing the Chester and Holyhead Railway, the idea fell, or dropped rather, for the time, in consequence of the expense of wrought-iron rather exceeding that of cast. On undertaking the Chester and Holyhead Railway, you will all remember that the original designs for crossing the Conway River and the Menai Strait were by cast-iron arches of very large dimensions, from 400 to 450 feet span. The execution of the latter work over the Strait would have been one, under any circumstances, of extreme difficulty, and would have required the utmost facilities to be afforded by those interested in the navigation of the Strait. It is familiar to you all that that project or proposal met with a strenuous opposition, whether reasonable or unreasonable it would be very improper in me to stop here to discuss. But it is sufficient to say, that parliamentary powers were granted for the construction of a bridge over the Britannia Rock, with such conditions attached to it as rendered it all but, if not absolutely, impracticable. It was then, to use a common expression, that I felt myself 'fairly driven into a corner.' No existing species of bridge was at all applicable under the operation of the Act of Parliament as granted; and it was after an anxious investigation of every possible description of bridge that it occurred to me, that by reviving the old notion of seven years ago, and by extending it, it might enable me to get over the difficulty. Approximate calculations were immediately made, and the result of those calculations was such as to satisfy me of the perfect feasibility of the work. And I well remember, when going into the Committee of the House of Commons afterwards, when a change in the direction of the line was applied for, and when the description of the bridge was to be announced, on explaining it to the committee, and giving it in evidence,—I well remember, I say, the surprise and the incredulous glance that I received from all parts of the room. However, I had satisfied myself that the thing was practicable, and I stood by it. As soon as the bill was obtained, and it became time to commence, I obtained the consent of the Directors to institute a very laborious, and elaborate, and expensive series of experiments, in order most thoroughly to test experimentally the theory I had formed, and also to add suggestions for its full developement. It was then that I called in the aid of two gentlemen, eminent, both of them, in their profession, Mr. Fairbairn and Mr. Hodgkinson. They had both distinguished themselves for elaborate series of experiments on cast-iron bridges, and, although this was a different material, still from their accomplishment and skill they were well qualified to aid me in my research. They heartily went into it, and the result is what you now see under the walls of your venerable old Castle. But having mentioned these two names, there is another gentleman that I wish to call to your notice—a gentleman, to whose talents, to whose zeal and ability, from the commencement of this undertaking, I am much indebted; and, indeed, the full developement of the principles of tubular bridges is by no means in a small degree indebted to him—I allude to my assistant, Mr. Edwin Clark. He has been my closet companion from the commencement of the preliminary investigation; no variation or inconsistency in the experiments eluded his keen perception; he was always on the lookout for contingencies that might affect the success—though not the principle, still the success—of the undertaking; and he and the other gentlemen whom I have just named, are the three to whom I feel deeply indebted for having brought the theory I first broached to such perfection, and I thus publicly tender them my acknowledgments."

CHAPTER II.

THE CONWAY BRIDGE.

Construction and Erection of the Second Tube.

The construction of the second tube proceeded rapidly on the removal of the first from the platform, and in seven months it was completed and floated. The most remarkable feature in its rapid construction was the use of a punching-machine constructed by Mr. Evans, and under his directions by Mr. Roberts of Manchester; it resembled in principle the ordinary Jacquard machine: a powerful shaft between two heavy cast-iron standards gave vertical motion to a line of punches through the medium of eccentrics on the shaft, which was driven by a steam-engine; thus, if all the punches were in action, a series of parallel rows of holes would be punched through any plate passed through the machine, the distance of each row being regulated by a ratchet movement. As most of the plates required only two rows along each side, and three transverse rows at each end, it was necessary, as the plate passed through, that only such punches should be allowed to descend as would correspond with the required holes. The throwing in and out of gear of the requisite punches was effected by a most ingenious application of a revolving pattern, as in the Jacquard loom. A full description of this machine will be found in Part 131 of "The Civil Engineer and Architect's Journal." And when it is necessary to punch a great number of plates to the same pattern, the saving in time and expense is decidedly very great, while the work is punched with an accuracy which cannot be imitated by hand.

Two men were employed in adjusting the plates to the sliding table, which passes them beneath the punches, and two others in removing them after they had passed through the machine. In this manner the bottom-plates for the tube, which were half an inch thick, and required 144 holes, $1\frac{1}{8}$ inch in diameter, were punched at the rate of 22 plates, or 3168 holes per hour.

The cranking of the angle-iron was entirely superseded in this tube by the use of packing strips, and the plating generally was more accurate. Otherwise the work proceeded precisely as before, and the camber of the tube was ascertained on September 23d, previous to cutting away the platform. The rise at the centre was 8·44 inches. The curve was very irregular as before, owing to the shifting of the platform. The curve at the top was also exceedingly irregular from the same cause.

SECOND TUBE, OR DOWN LINE.

Original Camber of the Bottom of the Tube.

Distance from Conway End.	Camber.	Camber.	Distance from Chester End.
Feet.	Inches.	Inches.	Feet.
0	0	0	0
22	1·0	1·29	22
44	1·99	2·70	44
66	2·90	3·59	66
89	4·54	4·94	89
111	5·80	5·80	111
133	6·72	6·60	133
155	7·59	7·47	155
178	8·15	8·49	178
200 (Centre.)	8·44	8·44	200 (Centre.)

Previous to the removal of the platform, which was accomplished in a much easier manner than with the first tube, preparations were made for observing the motion in the cast-iron frames occasioned by the deflection of the tube. This was done by suspending a plumb-line between the vertical pillars of cast-iron in the sides, and carefully observing its position before and after the removal of the timber.

It was not considered requisite to test this tube previous to the floating, as it was in every respect similar to the first, and the deflections were also so nearly alike.

The general arrangements for floating were also similar, and will be understood on reference to Plate XXXIV., in which they are shewn in detail. The principal feature in the Conway floating was the use of guide-chains, shewn in the Plate, consisting of two heavy chain-cables attached to moorings near the Suspension-bridge, and hauled as tight as possible at the other extremity by powerful crabs with messengers. These chains passed over the decks of the two outer pontoons through hawse-pipes in the timber of the boats; in each of those boats, moreover, there were crabs worked by twenty-four men, so that by means of messengers continually attached in advance on the chain the floating tube was hauled up these chains against the current, as with an ordinary ferry-boat. It was, however, found impossible to work these crabs with sufficient speed, and the chain became a useless encumbrance, and gave infinite trouble by breaking away from the buoys which supported it and fouling among the rocks at the bottom, and impeding the motion of the pontoons, which were drawn into their position almost by the capstans alone.

In addition to these chains, a mooring is shewn on the sand-bank under the Castle. The line passing from this mooring was secured to a timber-head in the interior of the tube, so that this line became a radius, on which the tube oscillated from its original position to the shelves in the towers. In order to ensure the action of this radius, and prevent the tube from drifting too near the Castle, it will be observed that a cable from a capstan in the eastern pontoons is attached to a mooring composed of chains and rails, on the bank of silt at the right hand of the Plate.

This mooring was, therefore, considered an important one, and, from its peculiar position, occasioned a great deal of labour. Many attempts were made to drive piles in this position without success; for although the silt is hard and compact at low-water, when covered by the tide it is almost a floating mass. At low-water, therefore, piles were driven to the depth of 7 or 8 feet with great labour, when it became impossible to drive them any farther, and they were apparently immovably firm and secure. As the tide rose, however, to some depth over the bank, they were drawn from the silt merely by their own buoyancy and floated away on the surface of the water. Attempts made to remedy this by weighting them were equally unsuccessful; but the system adopted of lashing together fagots of rails, as shewn in the Plate, was found perfectly efficient.

The moving power by which the tube was drawn against the current consisted of two capstans, one fixed beneath the first tube near the Castle, and the other on the embankment near the Chester Pier. They were each manned by fifty men. The capstans were 3 feet in diameter, and the ropes were 10-inch white manilla hemp, untarred, to assist its buoyancy.

A rope cable, moreover, from the capstan in the western pontoons, attached to the mooring beneath the Castle assisted in this operation.

A sixth cable from a capstan at the left-hand corner of the Plate, which may be considered as a variable radius, served to ease the strain on the fixed mooring, and, as the tube neared its place, was indispensable, for the sure adjustment required laterally for passing between the towers, only four inches of clearance at each end being allowed in the construction.

As soon as the tube had entered its place, crabs at each tower were used for any other adjustment that might be required. Lashing chains secured the pontoons in their position beneath the tube, more especially previous to their taking a bearing. Experienced superintendents were placed in charge of the men at each of the capstans, and instructions were conveyed to them from the top of the tube, under Mr. Stephenson's directions, by means of signals previously arranged.

The total number of men on each set of pontoons, including men at the pumps, valves, crabs, &c. was seventy, and about two hundred others were required to man the capstans on shore.

In case of accident, several boats' crews were also in attendance, and life-buoys were liberally distributed over all parts of the work.

The tide selected for the operation was a 17-feet tide, or as near as possible to that height, the level of the permanent rail in the tube when fixed being 21 feet 6 inches. The probable tide to be expected was estimated from the ordinary Liverpool tables, the previous day's tide at Liverpool agreeing very approximately both in time and height on the Conway tide-guage with the succeeding day's tide at Conway.

But heavy rains had increased the fresh water in the river for some days previously. On the morning of the 12th of October, which was the day of floating, the westerly winds which had prevailed had also increased the height of the tide; and it was evident, from the observations on the 11th, that there would be a 17-feet tide on the 12th, although, without these circumstances, a 16 feet 5 inches tide only would have been expected. Every preparation was accordingly made for floating, and on the morning of the 12th, at a quarter past eight, the pontoons began to bear against the tube. The weather was calm, but the rain in the night caused a good "fresh" in the river.

The tube when floating was 6 feet 6 inches above the water, the immersion of the boats being 4 feet 8 inches. It was raised from the temporary piers at five minutes past nine. By half-past nine it had risen 1 foot 9 inches above the piers, and signals were made to cut away the land attachments, and the crabs in the pontoons and the capstans at the Chester end were set to work.

Subsequent operations will be at once understood by reference to the Plate. The principal work was done by the two capstans on the line in hauling the pontoons against the current, which, though violent at first, began rapidly to slacken, and, at a quarter past ten, the moment of high-water, the river was as quiet as a lake, and the Holyhead end passed into its recess above the shelf prepared for it, and in eight minutes more both ends were in their place.

The tide was now running out to sea, and maintained the tube in its position as it was gradually lowered. To expedite the settling down of the tube on the shelves the valves in the bottom of the pontoons were opened, and about 18 inches of water admitted, so that by twenty minutes past eleven the tube settled on its bed, and in course of time, as the tide continued to recede and liberated the pontoons, they were at length torn violently away from beneath the tube, and, drifting beneath the suspension-bridge, were checked by means of anchors let go for the purpose, and with the assistance of a steamer were towed into a safe position under the town.

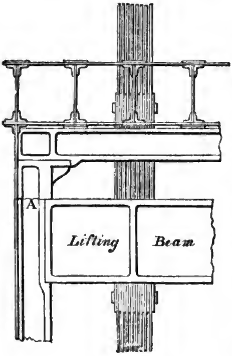
The following levels will explain the vertical rise and fall of the tube during the operation. The datum is the level of the surface of the rail in the permanent way, corresponding with 38 feet 6 inches on the local tide-guage.

	Ft.	In.
Bottom of the tube when resting on the temporary piers	21	0
Stone shelf in the permanent piers, including 18 inches of timber packing	19	6
Ultimate height to which the tide rose	17	2

The rate of rise of the tide will be seen from the following observations made on that day:—

Time. H.	Height of Tide. Ft.	In.	Time. H.	Height of Tide. Ft.	In.	Time. H.	Height of Tide. Ft.	In.
9 A.M.	14	6	9·40	16	7	10·20	17	1¾
9·5	14	10	9·45	16	9	10·30	17	0
9·10	15	1	9·50	16	11	10·40	16	10
9·15	15	6	9·55	17	0	11·0	16	2
9·20	15	9	10·0	17	1	11·20	15	5
9·25	16	0	10·5	17	1½	11·40	14	5
9·30	16	3	10·10	17	2	12·0	13	3
9·35	16	5	10·15	17	2½			

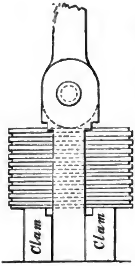
The Raising of the Second Tube.



The raising of the first tube had been so easily accomplished, that little difficulty was anticipated with the present one; but, in keying the lifting-beams in the frames at the Chester end of the tube, an operation which required great care to ensure an equal bearing on each of the four beams, one of the side-frames was broken, as at A in the sketch annexed, too much stress having been put upon the upper beams previous to keying up the lower pair. Mr. Stephenson, who was present, did not think the fracture of sufficient consequence to delay the progress of lifting, and proceeded to test the remaining frames by weighting the valve in the feed-pipe, so as to limit the action of the press to a strain of 350 tons; but in this operation two more of the side-frames were broken. It became, therefore, necessary to repair these frames, which occupied three or four days, and which was done by means of a saddle placed over the upper pair of lifting-beams and strapped down by wrought-iron links to a plate riveted to the frames. The tube was secured in this manner at both ends, and on the 30th of October was raised 3 feet, and then a 6-foot lift was made in less than 40 minutes. The pressure in the steam-cylinder was 21 lbs. per square inch, the engine making 20 strokes per minute, each stroke throwing two pumps into the press. The press on the Conway side leaked considerably, as before, the water oozing through the iron. The lifting-beams shewed considerable strain, having nearly ¼ inch of deflection, but the masonry did not appear disturbed. It blew a gale of wind during the operation, but the tube did not vibrate to any extent. Another stroke of 6 feet was then made, and immediately before its completion, with no efficient packing beneath the tube, it was discovered that the cross-head of the press was beginning to fail, there being an evident fracture in the top, several inches in length, which opened and closed as the strain was varied, but was invisible when all strain was removed. It was, however, imperative to complete the stroke, and, the chain being secured by the clams when it was accomplished, all danger was at an end.

The alarm which so providential an escape occasioned was, however, more durable; and this incident led to a complete modification of the lifting apparatus at the Britannia Bridge, and to the tedious precaution adopted by Mr. Stephenson of under-building the tube with brickwork, which, in August 1849, miraculously prevented the destruction of the bridge. Had the fracture in the Conway cross-head extended throughout the casting, not only would the tube itself have been destroyed by the fall, and the navigation of the river impeded, but the sacrifice of life must also have been very serious, as many visitors were on the tube, as well as Mr. Stephenson himself and others engaged in the operation.

The tube was immediately under-built with masonry, and the remaining lift of 2 feet 3 inches was actually completed with a fractured cross-head on November 2d, the fracture extending three inches farther during the operation; but precautions were adopted to prevent the possibility of any accident in case of its complete failure, by wedging up the tube from beneath with timber, and blocking up the chain itself by means of folding wedges passed between the links, bearing beneath the next links on the chain, and resting on the clams beneath, as in the sketch.



On the 8th the tube was lowered to its permanent bed, and on the 2d of January, 1849, it was tested by the Government Inspector, a weight of 235 tons, distributed over 300 feet at the centre of the tube, causing a deflection of 1·4 inch, from which the tube recovered itself immediately on its removal.

Details of the deflection of this tube will be found on page 661.

The whole of the work, including the interior of the cells, was painted with two good coats of red-lead paint as it was put together. The outside was then painted with two coats in stone-colour, the iron being previously well scraped to remove the flakes of rust which formed on some of the plates. It had been proposed originally to paint the plates separately, previous to putting them together, to which Mr. Stephenson objected, on the ground of its preventing that complete union of the plates which is so characteristic of riveted work, in which the friction forms an important part of the strength. Experience, moreover, shews that plates are brought into such close contact by riveting, that no corrosion need be apprehended at the joints. Among rusty scrap-iron, old pieces of riveted work will be always found most sound at the joints, and iron hoops on casks seldom fail at the rivet when eaten away by rust elsewhere.

In order, however, to keep the wet from drifting through the joints of the side-plates, where not completely protected by the cranked covers, it has been subsequently found necessary, in repainting the tube, to use a putty of red and white lead, to render the joints perfectly water-tight, and the top of the tube has been covered by a corrugated, galvanised iron roof, as shewn in Plate XL.: this has been found effectual in preserving the top, which must otherwise, from its method of construction, accumulate a deal of water between the covers of the plates, which divide the top into a series of small pools.

Deflections.—First Tube, or Up-line.

Deflection measured externally on the angle-iron uniting the sides with the bottom :—

Tube resting on the Temporary Piers.

Date.				Deflection in inches.
1848.	Jan.	8	Tube on the platform	0·
		25	Platform beneath cleared away	7·94
		26	50 tons over 50 feet at the middle	8·37
			Left on all night and removed	8·00
			90 tons over 90 feet	9·25
			Removed	8·5
		27	95 tons over 90 feet	9·31

Date.			Deflection in inches.
1848. Jan. 27	Left on one night and removed	11 A.M...	8·56
	154 tons over 140 feet ,,	5 P.M...	9·5
	201 tons over 180 feet ,,	5 P.M...	10·5
	201 ditto ,,	9 P.M...	10·5
28	201 tons left all night ,,	10 A.M...	10·62
	300 tons, 11 cwt. ,,	noon..	10·94
	Removed all but 11 tons		9·31
29	All removed	11 A.M...	8·81
	....	3 P.M...	8·62
Feb. 4	Rails inside removed		8·25*
Mar. 1	Ditto		8·06

Tube in its Permanent Position and Complete.

Deflection measured internally.

1848. Apr. 19	Tube without weight	0·
	150 tons ballast train, 200 feet at middle	1·6
	Test by the Government Inspector, Capt. Simmons.	
June 28	86 tons over 110 feet at the middle	1·02
	135 tons over 185 ,, ,,	1·08
	185 tons over 300 ,, ,,	1·08
	245 tons, nearly filling the tube	1·5
	Weight removed....................	0·18
	Train of 250 tons, and 2 engines, 15 miles per hour	1·08
	2 engines, weighing 50 tons, 25 miles per hour	0·6
July 5	Difference of deflection between noon and midnight	1·56

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* Deflections at other parts in the length, Feb. 4, 1848.

Tube clear of weight.

Distance from Conway end.	Deflections.	Deflections.	Distance from Chester End.
Feet.	Inches.	Inches.	Feet.
0	0	0	0
50	3·68	3·9	50
100	6·25	6·03	100
150	7·84	7·75	150
Centre	8·25	8·25	Centre

Deflections.—Second Tube, or Down-line.

Deflection measured internally on the vertical transverse plates, which support the permanent way.

Date.				Deflection in inches.
			Tube resting on Temporary Piers.	
1848.	Sept.	26	Tube on the platform................	0·
	Oct.	6	Platform beneath cleared away, noon ..	8·15
			Ditto ditto 9 P.M...	8·95
		7	Therm. in cells sunny side, 77 Fahr. shady side 70 5 P.M...	8·24
			Temperature uniform midnight..	9·16
			Tube in its Permanent Position.	
	Dec.	15	156 tons over 300 feet at the middle, 10 A.M.	11·70
			Load removed 12 A.M.	10·40
			Tested by Captain Simmons.	
1849.	Jan.	2	Permanent way complete, no load	10·33
			52 tons over 62 feet at the middle	10·81
			112 tons over 133 feet ,, ...	11·31
			173 tons over 211 feet ,, ...	11·62
			236 tons over 297 feet ,, ...	11·73
			Weight removed....................	10·33
1850.	Jan.	28	Tube twelve months in use............	10·30*
			Ditto ditto 2 P.M...	10·40
			Train 100 tons, passing at 15 miles per hour	10·87

* Deflection at other parts of the length, Jan. 28, 1850.

Distance from Conway Extremity.	Deflections.	Deflections.	Distance from Chester Extremity.
Feet.	Inches.	Inches.	Feet.
0	0	0	0
22	1·3	1·48	22
44	3·62	3·65	44
66	5·15	5·42	66
88	6·80	7·09	88
110	8·06	8·28	110
132	9·13	9·12	132
154	9·78	9·16	154
176	10·25	10·30	176
Centre	10·30	10·30	Centre

The mean deflection of the two tubes immediately on removal of the platform was 8·04 inches, and 8·98 inches, after obtaining permanent set due to the strain.

The deflection, from additional weight placed at the centre, is ·01104 inch per ton.

Chronological Summary.

Date.			
1846.	May	12	First stone laid N.E. angle Conway Tower
1847.	Apr.	8	First rivet inserted in the Conway Bridge.
1848.	Jan.	8	First tube completed.
	Mar.	6	First tube floated.
	Apr.	18	First train passed through.
	May	1	Line opened to Bangor.
	Oct.	12	Second tube floated.
	Dec.	16	Opened for traffic.

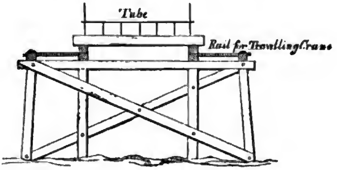
CHAPTER III.

THE BRITANNIA BRIDGE.

Construction of the Tubes.

The foundations of the Britannia Bridge were commenced on Good Friday, April 10th, 1846, and the masonry was already considerably advanced, when the platforms for two tubes were constructed in February 1847; but to expedite the work four platforms were ultimately commenced, it being thought advisable to complete simultaneously one span of double tubes to resist the effect of wind, rather than run a single line across the Straits, and with two platforms the time of construction would thus have been much prolonged.

The platforms were occupied by the month of July, and the first iron rivet inserted by the Author on the 10th of August, 1847. A section of the Britannia Platform is shewn in the sketch below.



These bays are 27 feet apart, the piles are set in the rock into which they are wedged; it was necessary to weight them to prevent their being lifted by the tide before the tube came upon them. The balks are mostly 14 inches square, the diagonal bond consisting of half balks.

It was found that these distant and massive principals were quite as inconvenient as the forest of small uprights at Conway, from the bending of the lengthy longitudinal timbers under the weight of the plates, and it was, again, impossible to keep the work straight. The constant strengthening of the platform was very troublesome. The weight of the tube, moreover, crushed the longitudinal timbers upon the principals, and they became so distorted as to endanger their stability.

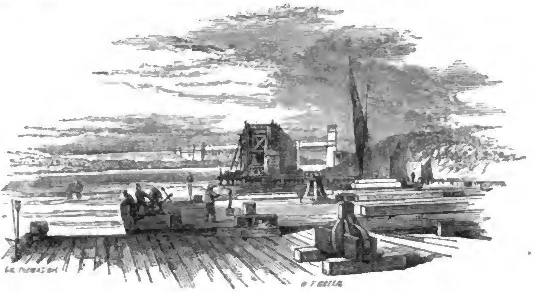
It will be seen, in Plate I., that the total length of this platform is 733 yards; and as there were no diagonal struts in the direction of the length, the principals being all parallel with each other, were slightly rocked to and fro by the contraction and expansion of the tubes. This constant motion, coupled with an accidental bias in the majority of the bays, led to a leaning of the whole platform, from end to end towards Carnarvon, which so far increased as to create at length some alarm as to its safety.

The danger was easily removed by the addition of a few struts, but the removal of the longitudinal timbers which were crushed by the tube, and the substitution of fresh ones, was a tedious and expensive process. The settlement had gone so far as to take out all the camber, or rise of 9 inches, given to the bottom of the tube, which had to be restored by lowering the extremities while the centre was supported, an operation in which many thousand wooden wedges were consumed, and the truth of the work somewhat interfered with. The sides were, of course, not yet put together.

Besides the immediate platform on which the tube itself rested, it will be seen, in Plate I., that a large portion of the beach was covered with staging for the convenience of workmanship, and the storing away of the plates as they arrived, and as they were sheared and punched.

A tram-way from end to end gave convenient access to all parts of this staging, which covered nearly 3½ acres of ground. A rail was laid on each side the tube for the travelling-cranes used for raising the plates, one of which is faithfully portrayed in Plate III. A powerful landing-crane between the first and second tubes was employed for discharging the iron from the vessels, and three large workshops were erected, each containing a steam-engine, with the necessary shafting, for driving the punching and shearing machines, flatting rolls, rivet-making machines, and fans for supplying blast to the furnaces.

At the further extremity of this platform, beyond the part included in the map, the launches for the repairs and construction of the pontoons were placed, and beyond these again lay the fleet of wooden pontoons that arrived from Conway. The whole length of beach thus occupied, extending from the stone wharf at the Carnarvon Tower to the pontoon dock at the opposite extremity, was 1000 yards, or nearly three-fifths of a mile. The pontoon-dock at the extremity of the platform is represented in the accompanying vignette.

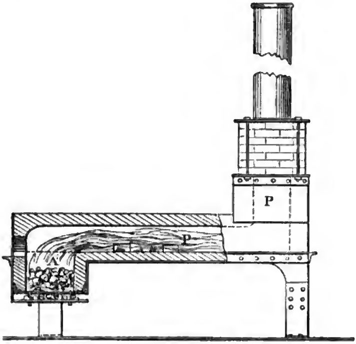


The busy scene which characterised this extensive area from end to end is well illustrated in the Plate before referred to; the temporary sheds, constructed with bars of angle-iron, beneath which each group of workmen was sheltered, the numerous rivet-furnaces, the novel appearance of the tubes themselves, in connexion with the bold rock which overhangs the work, form a highly picturesque subject for the artist.

The quantity of timber in these platforms is 110,105 cubic feet.

The routine of construction was of the same nature generally as at Conway. The most important points of difference will now only be alluded to.

The riveting was wholly hand-riveting, and the heating of the rivets was accomplished by means of an air-furnace, a feature of some novelty in this kind of work. The furnace will be best described by the following sketch:



A is the furnace, in which ordinary coal is consumed: the flame and heated current from the furnace pass through the passage P, P, which is lined with fire-brick. The rivets are inserted through a slide at the side, they lie on the bricks with which the furnace is lined, which together with the rivets themselves, are kept constantly at a red heat. These furnaces are most convenient where rivets are rapidly used, but they become burnt by remaining too long in the furnace. The floor is kept perfectly clean, to prevent, to some extent, the burning of the rivets. Each of these furnaces consumes 10 cwt. of coal per day, heating about 1000 rivets.

About forty-eight of these furnaces were stationed at different parts of the platform.

In constructing the bottom of the tube, the rivets were handed by the rivet-boys to the workmen, by means of iron pincers. As the work proceeded they were thrown on to the riveting platform; and so dexterous did the boys at length become, by the constant practice of throwing the rivets higher and higher as the work proceeded, that ultimately, although weighing 1¼ lbs., these red-hot bolts were thrown with extraordinary precision to the riveters on the top of the tube, at an altitude of 33 feet. In this manner they were also thrown into the cells at the top of the tube, and conveyed by other boys inside the cells to all parts of the structure, being inserted from the interior and riveted on the outside, while the holder-up was stationed in the cells.

In the construction of the interior they were passed through holes purposely left in the sides and drawn up to the top by a string attached to an iron ring, into which they were inserted.

As many as 7 or 8000 rivets per day were in this manner conveyed to all parts of the works.

The iron was brought from Runcorn and Liverpool by sea.

The plates were flattened principally by passing them between cast-iron rollers, instead of by the process of hammering. The buckle was effectually taken out of the cold plate by this process. The plates, thus flattened, were taken to the punching-table, which was a most effective contrivance for ensuring regularity in the punching, and superseded the *nursing* of the plate by a number of hands.

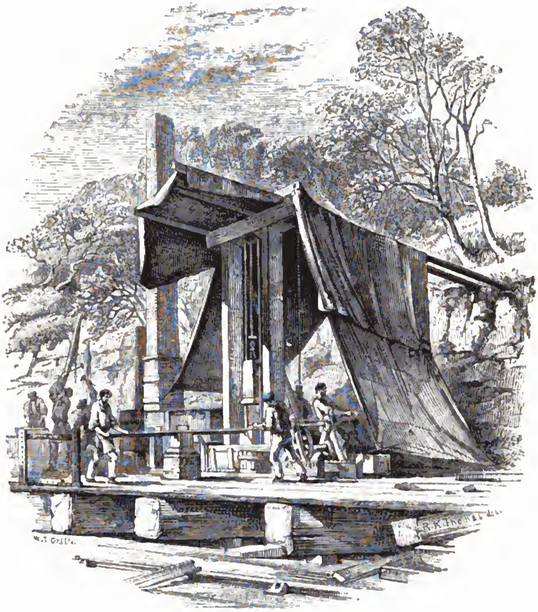
This punching-table is represented in Plate XXXI.; it consists of a cast-iron framed table, moving upon six grooved wheels on a Λ-rail, on which it passes and repasses in front of the punching-lever, just clearing the punch. Crank-handles, in connexion with gearing, give simultaneous forward motion to the wheels. The plate is secured on the top of the table by means of clamping-screws, the edge of the plate overhanging the table in such a manner as to pass immediately beneath the punch when the table is moved.

To regulate the distance of the holes the table is stopped at the proper intervals, by means of a ratchet attached to the underside, the teeth of which are at the intended distance of the rivet-holes. The table as it advances is retained by a catch dropping into the ratchet until the hole is punched; the catch is lifted by the return stroke, and the table again advances to the next notch in the ratchet.

The punching-machine in connexion with this table mostly employed at the Straits was the old tilt punching-machine, represented in Plate XXXI., and worked by an eccentric cam at the tail of the lever, on a shaft driven by the engine. The cast-iron jaws of this machine are liable to fracture, which appears generally to be the case with heavy castings, subject to continued, violent impact. Under such circumstances wrought-iron is peculiarly available.

Special shears were also used for cutting the angle and T-iron; and the cover-plates, instead of being smithed by hand, were cranked at a single blow, by a simple apparatus represented in the vignette.

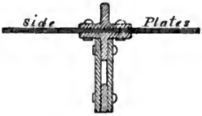
This machine consisted of a heavy monkey falling vertically between two uprights. The weight of the monkey was about 20 cwt.; and to the bottom was attached a cast-iron swage, corresponding with the required curve to be given to the plate. The swage fell upon a corresponding block below, on which the red-hot plate was laid, and struck into the required shape at a single blow.



The rivet and angle-iron was straightened by hand, the strikers often using a hammer weighing 40 lbs. with an accuracy and rapidity truly surprising.

The platers, riveters, and smiths, were mostly London men of great experience, the labourers being Welshmen; and the work was generally let by the piece.

On account of the great depth of these tubes, it was thought advisable to stiffen the sides immediately over the bearings upon the pontoons, the tube not being at all calculated for vertical support at any other part than at the extremities. Timber struts in the interior of the tube were used at Conway for a like purpose; but here, in addition to the timber, permanent stiffening plates of wrought-iron were riveted to the T-iron in the inside of the tube, forming vertical pillars between the top and bottom at right-angles to the sides. These pillars are formed of two half-inch plates, riveted on each side of the fin of the T-iron, with a strip between them, as shewn in the section below.



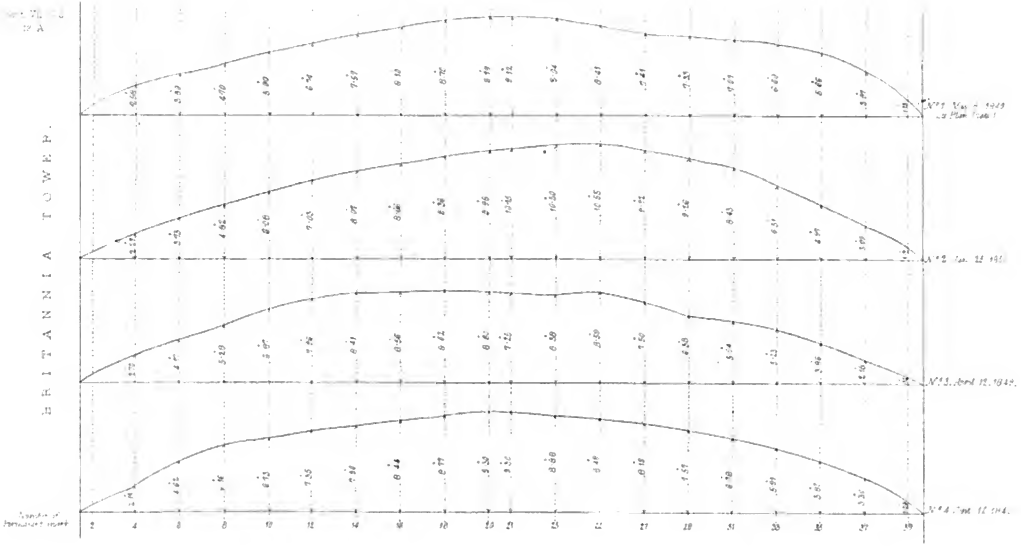
These additions were made after the first tube was completed, and, indeed, partially lowered.

Tube No. 3, in Plate I., was the first tube floated, and forms the Anglesey large span of the up line. The platform was completely removed from beneath it May 4th, 1849. The experience acquired at Conway had suggested a much better plan of removing the timber from beneath the tube, which was lowered gradually by the continual removal of blocks of deal, substituting other blocks of less height, which in their turn were cut away; and the tube thus descended from series to series, partly supported throughout its whole length, and without damaging the main timbers of the platform.

BRITANNIA BRIDGE.

Original Camber given to the Tubes measured from the vertical transverse plates on the bottom

NB. Vertical dimensions, in Inches



The camber given to this tube was 9 inches; its deflection in full sunshine, immediately on the removal of the platform, was about 10·25 inches; after sunset it was 11·2 inches. Its horizontal motion from changes of temperature was also very considerable. The camber of each of the tubes is represented in the accompanying Plate.

In all the tubes a considerable time elapsed before they attained a deflection which remained constant. Time is an important element in producing the ultimate permanent set in any elastic material; but when the permanent set due to the strain is once attained, the continuance of the same strain induces no further deflection, which is in accordance with the principles explained in a previous chapter, and is confirmed by the fact, that no subsequent change has occurred in the deflection of the Conway Bridge from two years of use, nor has any increase in the versed sine of the Menai Suspension-bridge taken place in twenty-five years, where the strain is greater than in the plates of the Conway Bridge, and liable to be considerably varied from the oscillation which occurs in gales of wind. The permanent strain in the Britannia Bridge is under three-fifths of that in the suspension-bridge.

The effect of time in producing permanent elongation has been also observed at the High Level Bridge, where the wrought-iron tie-chains, which resist the thrust of the arches, although under much less strain than the above, continued to extend for a considerable period before they attained a set at which they remained constant. These motions are so extremely minute that they are only ascertainable in large rigid structures, where they are measured by the corresponding increase of deflection.

Camber and Deflections. Mean of many Observations made at midnight, temperature equable.

UP-LINE—ANGLESEY LARGE TUBE, No. 3. (*See Plan, Plate* 1.)

	Britannia or High End.						Centre.	Anglesey or Low End.					
	Distance from Bearings.							Distance from Bearings.					
	Feet. 20	Feet. 44	Feet. 80	Feet. 116	Feet. 152	Feet. 188	Feet. 230	Feet. 188	Feet. 152	Feet. 116	Feet. 80	Feet. 44	Feet. 20
	Inches.	Inches.	Inches.	Inches.	Inches.	Inches.	Inches.	Inches.	Inches.	Inches.	Inches.	Inches.	Inches,
Original camber, or height above horizontal line....	2·16	3·45	5·03	7·40	8·29	8·90	8·15	8·31	7·35	6·67	5·52	3·74	1·38
1849, May 8. Deflection from its own weight after removing the platform ..	1·71	3·59	6·16	8·47	10·13	11·32	11·78	11·44	10·43	8·79	6·72	4·12	1·57
Nov. 15. Deflection when raised, and resting on its permanent bed	1·85	4·00	6·83	9·27	11·17	12·48	12·89	12·65	11·44	9·78	7·40	4·63	1·74
1850, Jan. 26. Deflection after joining Anglesey small tube, and lowering it 14⅝ inches	1·60	3·43	5·99	8·17	9·69	10·78	11·00	10·64	9·53	7·89	5·86	3·68	1·44
Feb. 6. Deflection after joining Carnarvon large tube, and lowering it 31½ inches	1·40	2·66	4·73	6·56	7·97	8·99	9·43	9·21	8·35	6·99	5·38	3·17	1·26
March 4. Deflection after joining Carnarvon small tube and lowering it 14⅝ inches	1·41	2·89	5·02	6·92	8·31	9·38	9·75	9·54	8·71	7·38	5·57	3·47	1·40

UP-LINE—CARNARVON LARGE TUBE No. 1. (*See Plan, Plate* 1.)

	Britannia or High End.						Centre.	Anglesey or Low End.					
	Distance from Bearings.							Distance from Bearings.					
	Feet. 20	Feet. 44	Feet. 80	Feet. 116	Feet. 152	Feet. 188	Feet. 230	Feet. 188	Feet. 152	Feet. 116	Feet. 80	Feet. 44	Feet. 20
Original camber, or height above horizontal line....	Inches. 1·84	Inches. 2·81	Inches. 4·54	Inches. 5·24	Inches. 7·53	Inches. 8·16	Inches. 9·00	Inches. 8·56	Inches. 7·15	Inches. 7·09	Inches. 4·46	Inches. 4½	Inches. 1·39
1849, June 6. Deflection from its own weight after removing platform......	1·69	3·56	6·09	8·24	9·97	11·11	11½	11·38	10·27	8·67	6·63	4·04	1·48
1850, Feb. 1. Deflection when raised and resting on its permanent bed-plates...............	1·80	3·82	6·46	8·71	10·46	11·64	12·25	11·82	10·62	8·96	6·84	4·22	1·61
Feb. 6. Deflection after junction to Anglesey large Tube, and being lowered	1·28	2·70	4·68	6·44	7·99	9·04	9·90	9·80	8·86	7·52	5·92	3·58	1·35
March 4. Deflection after joining Carnarvon small Tube, and lowering it ..	1·15	2·43	4·28	5·80	7·09	6·00	8·56	8·32	7·44	6·36	4·87	2·92	1·25

	Inches.
The mean deflection of the two tubes immediately on removing the platform, was thus ..	11·75
The mean deflection after being raised	12·57
Mean amount by which this deflection was decreased by uniting the tubes	3·41
Mean deflection of each tube permanently fixed	9·16

Deflection of Tubes No. 2 and No. 4. (See Plan, Plate I.)

Tubes resting on the Temporary Piers. Bearing 8 *feet at each extremity.*

		Inches.
Tube No. 2.	Original camber on the platform ..	10·06
	Deflection from its own weight....	10
Tube No. 4.	Original camber on the platform ..	9·3
	Deflection from its own weight....	11·16

The Tube No. 2 is still resting on the temporary piers preparatory to floating it; the diagrams of daily change of deflection given in a subsequent page were traced by this tube. Tube No. 4 has been successfully floated and raised, and will be connected laterally with No. 3, to prevent deflection from the effect of wind.

CHAPTER IV.

THE BRITANNIA BRIDGE.

The Floating and Raising of the First Tube.

THE arrangements for floating had engaged Mr. Stephenson's attention during the latter part of the year 1848; and the cutting away of the rock beneath the tube No. 3 on the plan was let in January 1849, and proceeded simultaneously with the removal of the platform and the completion of the tube at the ends.

The measurement of the large spans was again repeated by floating rods from back to back of the recesses, as at Conway. The results were as follows :—

ANGLESEY SPAN.

	Ft.	In.
Measurement 1.	470	10·00
2.	470	10·12
3.	470	10·50
4.	470	10·24
Mean	470	10·21

CARNARVON SPAN.

	Ft.	In.
Measurement 1.	471	5·37
2.	471	5·75
3.	471	5·12
Mean	471	5·41

The depth of cutting beneath the tube was 17 feet, the level underside being at 21 feet 8 inches on the tide-guage, which, it was hoped, would keep the tube clear from the highest tides; but the high springs of the 10th of January rose to 22 feet on the guage, and flooded the lower cells, which were afterwards, with considerable expense, flushed with fresh water, to prevent the oxydation as far as possible.

In order to arrange the programme for floating, Mr. Stephenson had a model prepared of sufficient dimensions for laying down the various rocks and cuttings. The scale was 6 feet to an inch. The pontoons and tube were made to the same scale; and by constant rehearsals of the process on this miniature pool the plans for floating were matured.

The stability of the tubes on the pontoons had been proved at Conway, and was again evident in the model. The requisite strength and length of the ropes were thus settled, and the positions of all the capstans determined.

The velocity of the current at starting was estimated at 1·8 miles per hour, diminishing gradually until the moment of tide-turn, when the water becomes perfectly tranquil. The tube is thus carried along by the tide, which is the only moving power, and restrained from attaining too great a velocity by means of the apparatus hereafter described. The object in view was principally to prevent the tube from attaining a velocity which it might become impossible to arrest, and at the same time to arrive at the ultimate position before the turn of the tide, which remains stationary only about ten minutes, and rapidly acquires a velocity of several miles per hour in the opposite direction.*

The tide, however, continues to rise for some considerable time after the current has changed its direction; so that, provided the tube be moored in its permanent position before the current changes, all danger is over, and abundant time remains for any subsequent adjustment.

The greatest pressure which it was calculated the stream would exert, supposing the pontoons at rest, was 14 tons, the eight boats presenting a surface of 400 square feet to the water, and the maximum motion of the stream being 9 feet per second. It was intended to limit the floating mass to a velocity of 1 foot per second.

* See a minute account of these tides in a subsequent chapter.

The pressure was calculated from the principle, that the force of a stream against a flat surface is equal to the weight of a column of water whose base is equal to that surface, and whose height is the height due to the given velocity. The theoretical effect thus obtained falls short of the actual effect on account of the absence of pressure before the boats in the wake caused by the current.[*]

The actual time in which it was necessary that the operation should be performed was thus limited to about an hour and a half.

The distance the tube had to float in this space of time was 1600 feet, besides an allowance for the delay necessary in hauling the tube out, and taking on board during its progress the ropes with which its final position was secured.

The object naturally was to obtain as much time with as little current as possible. The current being stronger in proportion to the height of the tide, rendered low tides advisable; while, on the other hand, low tides involved the cutting away of a great deal more rock beneath the tubes, for admitting the pontoons, and more packing upon the pontoons, which endangered their stability; and if this was remedied by lowering the tube on the temporary piers, and thus starting at a lower level, not only was the risk of deluging the tube with salt water incurred, in case of any delay, but the permanent shelves of masonry at the base of the towers would then also require to have been lowered. The highest tides, therefore, consistent with a moderate velocity, were selected, and preparations were made for tides of about 17 feet. Now, the level at which the tubes were constructed, which was 21 feet 8 inches on the tide-guage, for the purpose of avoiding the water during the construction, was too high for the operation of floating with an 18-feet tide, and a very considerable quantity of packing would have been necessary on the pontoons. To remedy this, the first operation was to lower the tube 2 feet on the temporary piers on which it was constructed; this was easily done at a previous tide, by bringing the pontoons beneath the tube some time before high-water, and, while the tube was supported on the pontoons, the timber packing placed beneath it was removed to the depth of 2 feet, and as the tide descended the tube was deposited on a lower level. This was accomplished on Monday evening the 18th of June, preparatory to floating on the 19th. The arrangements for floating will be easily understood by reference to the Plan, Plate I.

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[*] We have height due to velocity $=\frac{v^2}{2g}$, or $=\left(\frac{v}{8}\right)^2$; $\therefore$ height $=\left(\frac{9}{8}\right)^2$ $= 1{\cdot}25$ feet; and since a foot of water weighs 62 lbs., 1·25 feet = 77·5 lbs., and $400 \times 77{\cdot}5 = 31000$ lbs. = 13·8 tons.

First, two 12-inch untarred hempen ropes, each 1000 yards long, called outer and inner guide-lines, were attached to a sunken mooring opposite the fourth tube; they were then led through hawse-pipes, across the pontoons, to two capstans, as shewn on the Anglesey shore. They were partially buoyed up by casks, and the object of the capstans was, in the first instance, to keep them as taut as possible; and lastly, to serve them out rapidly as the tube moved round in the positions Nos. 7 and 8.

They were laid out with the rest of the lines on the morning of floating by crews of sailors, under the immediate direction of Captain Claxton, to whom the management of all nautical matters was here confided by Mr. Stephenson, as at Conway.

As these two lines passed over the decks of the pontoons they were served through cable-stoppers attached to the decks, and represented in Plate XXX. These convenient machines were a new feature in the Britannia operations, and answered most admirably the purpose for which they were intended. By means of capstan handles, worked by four men, any degree of pressure might be put on the lines, from a moderate friction up to a sufficient compression to break the lines themselves, if requisite.

As the floating mass descended down these guide-lines it was checked with the greatest facility by these clams, which may be regarded as gigantic hands for passing the pontoons down the lines with any required velocity. As these guide-lines only come into action after the tube is somewhat advanced, and as it was of paramount importance to avoid any risk of the pontoons fouling at starting against the side of the cuttings prepared for them, a strong chain cable, $1\frac{7}{8}$ inches in diameter, marked "radius chain," was attached to the same mooring as the guide-lines, and, passing inside the tube, was there secured by three or four turns round a transverse timber-head across the tube, and by lashings, which were cut by men stationed inside as soon as the tube had veered out sufficiently to clear the beach.

For the purpose of hauling the tube out as soon as it was lifted, two 8-inch lines, attached to moorings on the Anglesey side of the Straits, each of them 550 yards long, were buoyed across the water, leading through hawse-pipes and cable-stoppers on board the outer pontoons, to capstans fixed on board. This was sufficient preparation for the greater part of the journey; but the ultimate placing of the tube required much more complicated arrangements.

Four powerful capstans, marked E, A, C, H, were erected on wooden platforms on the beach, and lines leading from them were attached to buoys moored in the current in the positions shewn in the plan. Their object will be best understood from the programme of the operations arranged by Mr. Stephenson previous to the floating (pp. 685, 686).

All these capstans were fully manned by eleven intelligent superintendents, four hundred and fifty labourers, sixty-five sailors, and twelve carpenters. Each capstan had forty-eight men. The number of hands in each set of pontoons was one hundred and five, and six boats, with crews and spare line, attended the floating-tube in its progress. Two steamers were kept in readiness in case their services should be required.

The pontoons were completely equipped for the journey with pumps, tools, and spare rope. A ladder from each set led to the top of the tube, where Mr. Stephenson, in person, took charge of the operation, accompanied by Mr. Brunel and Mr. Locke, and assisted by Capt. Claxton, Mr. Wild, and the Author. Sir Francis Head, and Mr. C. J. Mare, the contractor for the tubes, were also on the top. The men at all these distant points were communicated with by means of signals from the top of the tube, which were very effective, and consisted of large letters corresponding with similar letters placed at each capstan. The holding up of any particular letter called the attention of the superintendent of that station to his signal. The waving of a white flag in conjunction with the holding up of the letter, signified "go on heaving;" a blue flag indicated "slack out;" and a red flag signified "stop heaving;" while the position of the flag indicated the rate at which the order was to be obeyed.

On the evening of the 19th, many thousands of visitors were assembled on either shore. The tops of the other tubes were also covered with spectators, seats having been provided for the purpose; and a stand was erected on the Anglesey shore for the Directors and their friends; every eminence was covered, and all waited with breathless anxiety for the order to start.

As the tide rose, and the pontoons began to bear against the tube, the deflection was taken out of it, and it returned partly to the original camber, which it had lost when the supports were removed.

The noise of the timber crushing beneath the rivet-heads, soon ceased, and at six P.M. it was announced that she was clear from the piers at each end, and the order was given by Mr. Stephenson to cut away the numerous land attachments by which the pontoons were secured in their places, and the "hauling-out capstans" were set merrily to work. Before proceeding many yards, however, the capstan in the Carnarvon pontoon gave way from the too great strain put upon it by so many fresh hands full of excitement. The spindle proved too weak for the temporary purpose for which this capstan was employed.

The accident deferred the operation, and orders were given by Mr. Stephenson to bring the tube home again, which was easily and rapidly effected, to the great disappointment of the numerous visitors now accumulated.

The wind was rather high at the time, and increased to a stiff breeze; and subsequent events gave no cause to regret this mishap.

The capstan was restored in the course of the night, and every exertion was made to float by the early tide of the next morning, when numberless visitors were again assembled, and destined again to be disappointed.

Though no great difficulty had been experienced in laying out the various lines as described at slack water, it was almost impossible to hold them as the tide rose and swept past them with a velocity of six miles an hour. The buoys were torn away from the lines, which, bellying in the current, dashed with fearful vibration over the surface of the water, lashing it into clouds of spray. The tension was so great, moreover, that it threatened to draw the pontoons from beneath the tube, and considerably shifted their position in spite of the numerous moorings with which they were lashed back.

The large boats attached to the buoys, with spare line on board, after plunging about in the current for some time, were dashed under, or torn to pieces. The heavy moorings to which the buoys were attached were dragged from their positions. Some of the lines were entirely carried away, and all the buoys so far shifted as to render them useless, and in spite of the strenuous exertions made by Capt. Claxton and his very able assistant, Mr. Whitting, it was found impossible to repair the damage which was done. Some little anxiety, indeed, began to be felt as to the possibility of moving with these tides; but, in the course of the day, by great exertions, the old moorings were replaced by heavier ones obtained by sinking some of the heavy castings of the works; the buoys were replaced, and by half-past seven in the evening, the tube was again afloat, and the spectators assembled, though in somewhat diminished numbers.

The tube floated 5 feet 3 inches above the water; on cutting away the land attachments she swung out like a monster pendulum upon the radius chain into the current. This heavy cable became apparently a straight line as the water boiled up along the broadside of the pontoons. Very little strain was put on the "hauling-out lines," which by bellying in the stream dragged the tube into the current.

The wind was rather brisk from the S.W., and the tide very strong, and as soon as the radius-chain was let loose from the interior, the tube fell back upon the guide-lines, which, in their turn, were dragged out of the water. The speed was now beautifully regulated by the cable-stoppers, by which the motion of the tube was restricted to from one to three feet per second. The guides were severely strained; the friction through one of the cable-stoppers at length wore it down, so that it ceased to bite the rope, and one line was more strained than the other; the velocity of the tube began, in consequence, to increase rather seriously as she neared the rock. The eight-inch "hauling-out line," which, by some neglect, was not slackened out, snapped like a pack-thread. On approaching the buoys, the greatest difficulty was experienced in getting the lines on board from the drifting of the tube too near to the Anglesey shore. The success of the operation depended mainly on properly striking the "butt" beneath the Anglesey Tower, on which, as upon a centre, the tube was to be veered round into its position across the opening. This position was determined by a twelve-inch line, which was to be paid out to a fixed mark from the Llanfair capstan.

The coils of the rope unfortunately over-rode each other upon this capstan, so that it could not be paid out; in resisting the motion of the tube the capstan was bodily dragged out of the platform by the action of the palls, and the tube was in imminent danger of being carried away by the stream, or the pontoons crushed upon the rocks. The men at the capstan were all knocked down, and some of them thrown into the water, though they made every exertion to arrest the motion of the capstan-bars. In this dilemma Mr. Charles Rolfe, who had charge of the capstan, with great presence of mind, called the visitors on the shore to his assistance, and, handing out the spare coil of the 12-inch line into the field at the back of the capstan, it was carried with great rapidity up the field, and a crowd of people, men, women, and children, holding on to this huge cable, arrested the progress of the tube.

Capt. Claxton had also in the meantime, with great rapidity, made arrangements for meeting the contingency. The capstan on the stage (H) gave some trouble in a similar manner, but the tube was brought safely against the butt and veered round.

The Britannia end was then drawn into the recess of the masonry by a chain passing through the tower to a crab on the far side. The violence of the tide abated, though the wind increased, and the Anglesey end was drawn into its place beneath the corbelling in the masonry; and as the tide went down the pontoons deposited their valuable cargo on the welcome shelf at each end. The successful issue was greeted by cannon from the shore and the hearty cheers of many thousands of spectators, whose sympathy and anxiety were but too clearly indicated by the unbroken silence with which the whole operation had been accompanied.

It was late before the tide was sufficiently low to allow of the drifting away of the pontoons from beneath the tube, although some water was admitted into them. This operation was attended with extreme danger to those on board, as the tide had now attained a fearful velocity in the opposite direction, and night was approaching. Many of the men on board, unused to operations on the water, became alarmed at the violence of the stream, and called out to be taken on shore, scrambling for the life-buoys, and in the utmost confusion, in spite of the efforts of the sailors and superintendents to quell their fears. These massive rafts at length tore away from beneath the tube, crushing the timbers, dragging the timber-heads and the pumps out of the decks, and increasing the fears of the terrified and crowded crews on board. They, however, glided away safely down the current in the dusk; some were brought to by the anchors with which they were provided, others taken in tow by the attendant steamers, while some defied all attempts to arrest their progress, and drifted down the Straits for nearly two miles, till they were stopped in the quiet harbour of Velin-heli.

It was midnight before all the pontoons were clear of the tube.

With the exception of an accident to a man on board one of the steamers, not engaged in the floating, not a single casualty characterised this gigantic operation.

The following programme, drawn out by Mr. Stephenson previous to the operation, will, in connexion with Plate I., explain every detail. Written instructions were supplied to all parties engaged, who thus acted simultaneously, in strict conformity with these arrangements.

OPERATIONS DURING FLOATING OF THE FIRST TUBE.

	Ft.	In.	
Pontoons with	2	6	packing.
Bottom of tube	5	8	above water.
Pontoons	3	2	ditto.
Draught	6	10	to bottom of keelsons.

Time, 7^h 40^m P.M. Speed, 1 foot per second.

The tide having risen to 12 feet 8 inches, the tube will be 2 inches clear of the temporary piers. Guide-cable stoppers being screwed down, haul out high end 80 feet, low end 120 feet, by capstans on iron pontoons; easing off land attachments round timber-heads on wooden pontoons, and tightening the guide by guide-capstans.

Cut away radius-chain and cast off land attachments.

Open guide-cable stoppers and slide down guides into position No. 3, length of permanent hauling-line remaining unaltered, letting out temporary hauling-line 40 feet (5 turns).

Pay out hauling-lines freely, continuing to slide down guide-lines until the tube drifts into position No. 4.

Attach line from Llanfair capstan (marked E on Plate I.) to timber-head at bows of iron pontoon, low end. Cast off temporary hauling-out line.

If the tube is inclined to drift too near the Anglesey shore, attach lines from stage timber-heads to stern of pontoons.

Drift into position No. 5, hauling in slack with the Llanfair capstan, still paying out permanent hauling-line freely.

At No. 5 attach line from Garforth's capstan (H) to timber-head at stern of low end iron pontoon; attach line from Spare Rock capstan (C) to iron ring at high end of tube; also attach line from Anglesey crane-capstan (A) to timber-head at stern of iron pontoon, low end of tube.

Drift down guide-lines from No. 5 to No. 6, during which time take in slack of lines from Anglesey crane and Spare Rock capstans, if requisite putting on a strain to increase speed; also pay out both guide-lines.

In position No. 6 the pontoons at low end will be held by lines from Llanfair, Garforth's (H), and Anglesey crane-capstans, and the high end will be held against the guide-lines by the line from the Spare Rock capstan. Here liberate outer guide-line from high end pontoons, and attach Anglesey Tower chain to ring on tube.

Slue round into position No. 7 (this position being determined by the tube *pointing to Garforth's capstan*) by Spare Rock capstan. The three lines fast to low end pontoons remaining untouched, but the two guide-lines being paid out rapidly through their cable-stoppers. If the friction caused by so great a length of the inner guide-line having to be paid out through three cable-stoppers should impede the operation of slueing round, close low end cable-stopper, and cut line close to it, paying out loose end through high end cable-stopper.

Attach line from Britannia capstan to ring on high end of tube, and chain from Anglesey crab to ring on low end of tube. Haul tube against butt by Anglesey crab, paying out line from Garforth's capstan (H), and when tube is home casting same line off.

Haul round tube against Britannia butt by Britannia capstan, paying out line from Spare Rock capstan, and also inner and outer guides.

Attach chain from Britannia crab to end of tube.

Throw off packing from permanent shelves to proper level for receiving tube.

Haul into Britannia recess by means of crab.

Haul back Anglesey end into recess by Llanfair capstan and permanent hauling line-capstan.

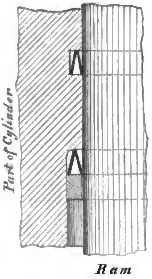
The Raising of the First Tube.

The tube reposed across the water, out of reach of the tide, during the remainder of June and the whole of July, while the raising machinery was fitted in the towers; and in the meantime the corbelling in the masonry was underbuilt. The two presses used at Conway were placed in the Britannia Tower. The new single press (see Plate XXVII.) was placed in the Anglesey Tower. The chains were raised in separate portions by capstans, and suspended from the crossheads. Rope-ladders from the tower to the top of the tube afforded a ready communication with the presses above; and on the 6th of August the chains were attached to the frames in the tube, and the delicate operation of keying up the lifting-beams was carefully performed. The large press was now tested. Two cylinders for this press had been already cast. An account of the defects of these castings has been given at page 618. In casting the second cylinder the mould was fed by channels in the pit leading to the bottom, so that as the metal rose, the scoriæ and the air were driven away before it.

On testing this cylinder, the upper part of it was found extremely leaky, the water oozing through the solid metal under the pressure nearly as fast as it was pumped into the cylinder. The bottom was sound. The principal leakage occurred at the guide-rod sockets cast in the top of the press; these soon filled with water, and overflowed the press.

The delay which this occurrence threatened was of great importance, as it interfered with the preparations for the floating of the next tube, and, consequently, the completion of the line; for it was requisite with the Carnarvon span that the presses should be removed, ready for lifting the tube as soon as it was floated, in order not to obstruct the navigation, which is principally confined to this Channel.

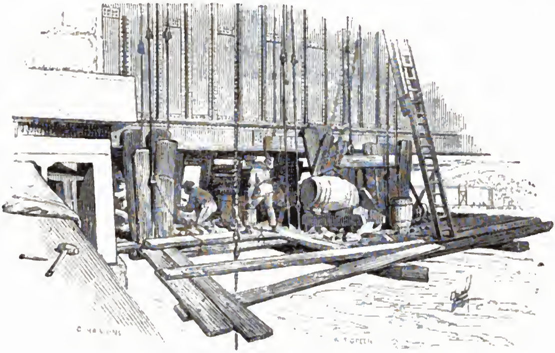
The cross-head and the ram were removed from the press, and every means adopted for remedying the leakage. The channel in the interior of the press which contains the leather collar, was carefully hammered, as it was found on plugging up the socket where the leakage occurred, and forcing water into the hollow left beneath the plug that the water came through into the press round about this groove; but the most important alteration that was made was the addition of a second leather below the first, which was done as in the sketch below.



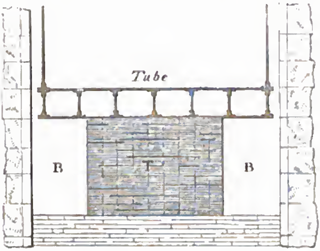
The lower leather thus cut off all communication with the porous metal in the upper groove, which appeared to be the cause of leakage. The press was, moreover, closed with oat-meal gruel and sal ammoniac, as described in page 619. In three days all this was accomplished, and the heavy cross-head and ram, weighing together more than 16 tons, were again in their place; and on the 10th, without much leakage, the Anglesey end was raised four feet.

The strain on all the parts of the masonry had lately been re-considered by Mr. Stephenson, and abundant strength was found everywhere. The joints were unmoved by the weight, and the only symptom of stress was the flaking-off of some small particles of the surface of the limestone immediately beneath the bearings.

On the 11th, the Britannia end was raised six feet with the double press. Mr. Stephenson had determined on under-building this tube as it was raised, by filling up the space between the buttresses by brickwork in cement. This was a precaution subsequently adopted, as it was originally intended to have depended solely on the presses until the tube was high enough for inserting the beams in the wall-boxes shewn in Plate IX., where a general view of the arrangements for raising is given. In order that the tube might never be without support, timber planks were inserted beneath it. For this purpose a platform was suspended beneath the tube, which was raised with the tube, as in the accompanying vignette; the space between the planks and the bottom of the tube never exceeding an inch.



The tube was raised six feet at a single stroke, and the timber was piled, as in the sketch below marked T.



At the end of the stroke the clams were closed, and the tube was thus suspended from the chains above, without bearing upon the timber. The spaces B B were then built in with brickwork. As soon as this was completed, the timber was removed, and the space T was similarly built in with brickwork. Thus a level bed was formed, and the raising proceeded by a repetition of this process.

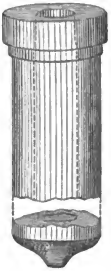
On Monday, during a violent gale of wind from the S.W., both ends of the tube were again raised six feet. With a moderate wind, the tube oscillated like a pendulum between the piers; but so great was the pressure from this gale, that an inch bar of iron, inserted between the tube and the side of the recess, to prevent the ploughing away of the masonry, was nearly cut through.

The friction against the side of the buttress to leeward slightly tilted the cross-head.

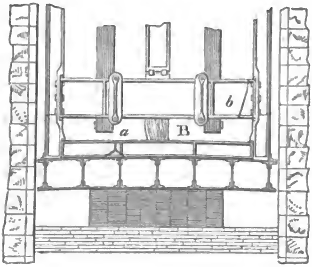
A singular phenomenon occurred with the wind, more especially before the tube attained its present elevation, — although the gale beat violently against the side of the tube, a complete calm prevailed all over the top. The wind appeared to be thrown off at about an angle of 45°, forming so complete an eddy, that a silk handkerchief, held out in the hand, hung almost motionless and perpendicular; and persons walking over in this comparative calm were surprised at the effect of the wind beneath as it lashed the water into spray.

The time occupied in lifting was about forty minutes, and this operation was performed in the morning, the brickwork being underbuilt in the course of the day.

The leakage of the press diminished, and everything proceeded satisfactorily until the 17th August, the tube being raised about 24 feet, when an accident occurred unparalleled in the history of engineering, the whole structure barely escaping destruction. On the morning in question, which was unusually calm, the presses were working with little leakage, and the engine labouring even less than usual, making about 26 strokes a minute, and lifting the Anglesey end, the other end resting on the brickwork beneath it. The Author was standing on the cross-head of the press, communicating, on the one hand, with persons on the top of the tube, about 100 feet below him; and, on the other hand, with his brother, and other persons in the tower, who were superintending the valves and the working of the engine. The ram was steadily rising, and about 2 feet 6 inches of the stroke was completed, when the bottom of the cylinder suddenly broke away from the body, and the cross-head descended with a fearful crash on to the top of the press, the tube itself falling on to the packing below. The Author was thrown into the interior of the tower without sustaining any injury; his brother, and several men who were beneath the platform attached to the cross-head, had a most miraculous escape from being crushed by its descent. The castings attached to the clamping-machinery were broken by the blow of the descending cross-head and chains, which weighed upwards of 50 tons. The clamping-screws were much bent, but though violently shaken, no important part of the machinery was damaged by the fall.



The bottom of the cylinder weighed about 2½ tons, and fell on to the top of the tube beneath. An unfortunate sailor, who was ascending the rope ladder immediately below, was thrown by its descent from a height of 60 feet on to the top of the tube, and survived only a few hours. The greatest anxiety was felt as to the fate of the tube itself, which, by the crushing of the timber packing, and the bending of the central portion of the bottom, had descended through a space of about 8 or 9 inches. Externally, no important injury was perceptible; the cylinder falling on to the top had broken in the top plates and made a deep indentation. The sides were slightly bulged out. The timber packing beneath, which occupied 8 feet 6 inches of the centre of the tube, was much crushed, and the brickwork beneath it was distorted by the weight. The bottom plates were bulged in to the extent of 3 or 4 inches, the curvature extending, visibly, for 40 feet along the tube. On examining the interior, which was accessible by means of a man-hole in the top, the damage done was found to be very serious, and the tube could not long have sustained itself in the position in which it was then placed. Some of the castings in the cells were broken; the three lower sills of the lifting-frames were all broken. One of the lower lifting-beams was broken, and the four side columns of the lifting-frames were all fractured immediately beneath the lower lifting-beams. The top of one of the frames was also broken by the fall of the cylinder, as well as nearly all the bolts and nuts for securing the castings. The tension rods connecting the side frames fortunately did not give way. The following sketch will give the positions of most of these fractures, where they are all brought into the same section.



The weight of the tube, it will be seen, was thus principally supported by the balk of elm marked B. A section of this prop, to illustrate the manner in which it was crushed, is given at page 369. The weight upon it was nearly 1000 tons, or half that of the tube.

Immediate steps were taken to secure the tube from any further motion. Iron plates were packed between the perfect lifting-beam and the bottom of the tube, whilst wedges upon the brickwork were driven beneath the sides of the tube. All attempts to cut away the timber in its compressed state under the tube were unsuccessful, and it was found much easier to cut away the brickwork itself beneath the timber, which occupied several days. The tube was thus ultimately supported under the sides alone, and the bottom partly recovered its shape.

The metal was rather soft or malleable, being easily indented by a blow. The fall of the ram on the top of the cylinder had riveted the iron to such an extent that it required a force of 100 tons to draw the ram from the cylinder.

Much discussion ensued as to the best form for a new cylinder; some argued that no cylinder of that magnitude could be depended upon, that in so great a thickness of metal the contraction and crystallization of the central portions could not be avoided, and that no cylinders would stand so great a pressure for any great length of time. The substitution of a double press, as employed at the other end of the tube, naturally suggested itself; but the disadvantages of two presses have been already alluded to. Under such circumstances, moreover, a fresh cross-head would have been required; nor was the masonry in the land towers adapted for the reception of such a system. Mr. Stephenson consequently decided on ordering a new cylinder in every respect similar to that which had failed, excepting that the mass of metal at the bottom was reduced in bulk, and the shape of the bottom was modified, as in Plate XXVII.

Two such cylinders were cast in case of another accident. They differ slightly in the form of the bottom, as shewn in Plate XXVII. The metal was first run on the floor, and then recast. Arrangements were also made, so that in case of another failure no injury might be done to the tube or to the parties employed. For this purpose a timber platform was placed immediately beneath the press, to prevent its descent on to the tube. The deal packing used underneath was changed to oak planking, the boards being an inch thick, to be inserted, not as before, under the centre, but in two piles beneath the sides, and to be always in close contact with the tube, and carefully packed.

In the incredibly short space of six weeks a new cylinder was cast and delivered from the Bank Quay Foundry Warrington, and in the meantime the tube was thoroughly repaired. A fresh lifting-beam replaced the one that was fractured. Iron packings were inserted between the lower lifting-beams and the bottom of the tube, which was partly forced back into its shape, and the end of the tube was entirely blocked up by pillars of oak placed between the other lifting-beams. Additional tie-rods were placed across the tube to counteract the bulging of the sides. The masonry was strengthened by similar tie-rods across the towers. The fractured sills in the frames were not removed until the tube was raised to its place, when two of them were replaced by new sills, and the third was repaired by wrought-iron plates riveted along it.

A new ram was cast, on account of the leakage of the first, through which the water was forced, filling the hollow inside, and overflowing at the top. The same phenomenon occurred, however, with the new ram, though both were perfectly sound, and the water appears to have been forced through the solid metal.

Arrangements were made in the tower for packing up the cross-head itself as it was raised by the press, by means of wrought-iron plates piled beneath it, on the top of the press around the guide-rods. The tube on several occasions was entirely supported by these packings, in conjunction with bars passing through the chain, as used at Conway, and before described.

On the 1st of October all these arrangements were completed, and the tube was again lifted, with no leakage through the cylinder, which appeared to be a perfect casting.

The tube was now raised 6 feet daily, at a somewhat lower speed than formerly. On the 6th it was 58 feet high, and the Fairy steamer passed beneath it. Some little trouble was given by the unequal action of the double press in the Britannia Tower, where similar precautions against accident were adopted; but on the 13th the tube safely attained its final elevation.

The deflection of the lifting-beams was one-eighth of an inch. The cross-head deflected the same quantity; but no perceptible deflection occurred in the wrought-iron beams that supported the press.

The adjustment of the bed-plates beneath the tube was performed as follows:—The tube was raised about 18 inches above the upper bed-plate, and secured in that position by packings beneath the cross-head, and also by packings upon the cast-iron beams inserted through the wall-boxes. The bed-plates were then moved forward into their permanent position beneath the tube, forcing away the plank packings before them, which were replaced as it receded by packings upon the bed-plates themselves, on which the tube was then deposited. In this position the junction-pieces in the towers and the land-junction, weighing 174 tons, were moved forward on a launch and riveted to the tube. The tube was again raised off these packings with the junction-pieces attached. The oak planks were removed from the top of the bed-plates. The layer of creosoted timber was covered with putty, and the tube permanently lowered on to the bed of putty. This operation was performed on the 10th November during a gale of wind, but the tube was kept central by iron guides on either side. The press appeared severely strained with the extra weight. The engine worked heavily, and the water leaked through the leather collars.

In little more than a fortnight after this operation the presses were removed ready for raising the next tube. They were lowered and raised again by means of capstans, with an 8-inch rope; and in this operation another accident occurred with the unlucky single press. The cylinder was lowered from a cat-head at the top of the tower, the rope from the blocks led to a capstan on the beach, on which three turns only were taken. While the cylinder, weighing 12 tons, was suspended at an elevation of 140 feet above the water, the rope unexpectedly surged on the capstan, and was dragged out of the hands of the men who were holding it; the cylinder descended with fearful velocity, dragging the rope through the block tackle and round the capstan, which fortunately became palled by the jerk. As the velocity increased, the cat-head in the tower gave way, and the cylinder fell on to the stone shelf below, fracturing the masonry, and gliding off fifty or sixty feet into the Straits. Several men were injured, and a sailor who was serving out the coil of rope was dragged round the capstan and killed. None of the tackle was broken, and the press was easily raised by the ropes attached to it, and was found to be uninjured by the fall.

CHAPTER V.

THE BRITANNIA BRIDGE.

The Floating and Raising of the Second Tube.

The day fixed for floating the second tube was Monday, the 3rd of December; and as high-water at spring-tide occurs early in the morning, the short length of the days was of little consequence, while the weather is generally as calm in December as in any month of the year.

This tube is marked No. 1 on the plan, and the site of its construction is nearer to the towers than any of the others. It had, in fact, only to travel a distance of 850 feet. The first operation preparatory to floating was the lowering of the tube 18 inches, by means of the pontoons, to a proper level for starting. This was done on Sunday the 2nd. The tides came in favourable, and the weather was calm and quiet, although wet. When the tide reached 12 feet 8 inches, the pontoons began to bear against the tube, and the rivet-heads to sink into the timber. The tube lifted when the tide reached 16 feet 3 inches, the extremities floating 5 feet 6 inches above the water. The tube continued to rise, with a vertical oscillatory motion of about 4 inches in 38 seconds up and down.

The packing was removed from beneath, and after being afloat about four hours the tide gradually lowered the tube on to the piers again. No water was let into the pontoons, as it would have endangered the stability. The strain of the tide against the lines leading across the Straits was again fearful, tending to drag the tube out into the stream, and additional messengers from the land were found necessary. Strong chains from each end were added, to prevent longitudinal motion, as the tide swept by with unusual strength.

The lines were laid across the Straits as follows: two 10-inch hauling-out lines to the opposite shore; one 12-inch guide-line from the Anglesey shore across the water, and over the pontoons to a stage erected 300 feet beyond the Carnarvon Tower. Also an inner 12-inch guide-line from tube No. 2, leading over the pontoons to the same stage as the former, the slack of both of them being taken in there by a powerful crab, with messengers worked by twenty-four men.

The tube, therefore, descended with the current between these two guide-lines being at the same time slightly veered round, until the end was brought in contact with a butt by the side of the Carnarvon Tower. It was then slued round as before, until the other end led fair into the recess in the Britannia Tower, where it was hauled in by a crab, and the other end was then drawn into its place by a capstan on the Carnarvon shore for that purpose. A $1\frac{5}{8}$ inch radius chain, as before, led from the end of the tube to tube No. 3, on which the pontoons swung out into the current. It was then served out from the interior of the tube, but kept in hand till the end of the operation. The guide-lines passed through hawse-pipes and cable-stoppers as before. The land attachments were secured to rings leaded into the perpendicular face of the rock in the cuttings, and signals as usual were placed at the different capstans. Instead of using buoys, which had proved so troublesome before, three small 6-inch lines from the capstans on the Britannia Rock, called *messengers*, were used to haul in the larger 12-inch lines as the tube approached.

On Monday morning every arrangement was complete, and again a large concourse of people was assembled. Mr. Stephenson, accompanied by Mr. Bidder and Mr. Brunel, and assisted by Captain Claxton, Mr. Wild, and the Author, were upon the tube. The capstans were all manned, and the tube began to lift, when one of the hauling-out lines which was being drawn in parted in the middle of the stream, and the operation was vexatiously delayed. The line presented every appearance of having been cut mischievously by a sharp instrument; but it had sunk to the bottom, nearly all the 32-gallon casks used as buoys being torn away from the line by the tide.

The wind, which was brisk in the morning, rose gradually during the day to a heavy gale, the barometer having fallen three-quarters of an inch in the previous forty-eight hours; but the sailors under Captain Claxton continued to work, and repaired all the damage that was done; and on Tuesday morning all was again complete. The morning was cold and damp; but as the time approached, the weather cleared up into bright sunshine, occasionally obscured by a slight fall of sleet. By ten o'clock the pontoons began to bear against the tube, and the chains and messengers used for keeping them steady were cut away. An attempt was made, without success, to take in some slack upon the guide-lines, which bellied considerably in the stream. Eighteen-gallon casks were found preferable to the larger ones used before; but many of these drifted away, as the lines danced in the current with a tremor which shook the pontoons.

The tube began to lift at thirteen minutes past eleven, and no time was lost in starting. All hands were ordered to stand by; and after a few minutes of breathless silence, Mr. Stephenson signalled for the land attachments to be slacked out. One of them failed as soon as the order was given, the iron bolt in the rock being dragged asunder from the tension on the lines across the stream; and without using the capstans, the tube glided quietly out into the current with a motion so smooth, that it was difficult to believe but that the shore itself, with its crowd of spectators, was receding from the tube. The hauling-out capstans, however, began their giddy round, and the tube soon dragged the ponderous radius-chain over the adjacent platform, while lashing after lashing, which had been used for laying it out, now tore away, and it fell with a crash into the water. The pontoons meeting the tide, however, soon brought it taut again, and thus swung out 120 feet into the Straits.

The radius-chain was now payed out at the end of the tube, the cable-stoppers on the main guide-lines were slackened, and the raft descended slowly with the current, as the chain surged round the timber head inside the tube and sunk again into the water. In the meantime the three capstans on the Britannia Rock, and the capstan on the Carnarvon shore, each manned with thirty men, began simultaneously to take in the slack of their long messengers as the tube approached them, and the busy scene increased rapidly in excitement and interest. The sun shone brilliantly; the tide was unusually quiet, and the speed impatiently slow.

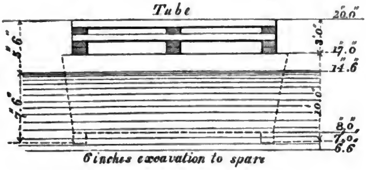
The tube was slightly checked by the cable-stoppers, to prepare for bringing a 12-inch rope into action from the Carnarvon shore, when it was discovered to be foul in the large block through which it was rove; and although two boats' crews of sailors, assisted by a gang on the pontoons, were immediately at hand, it was found impossible to remedy the disaster. The double line was therefore immediately converted into a single line by lashings for that purpose, and the tube continued its descent. This caused some delay, and rendered an additional strain necessary on one of the hauling-out lines, which had the effect of bringing the tube too far over towards the Anglesey shore. This was partially remedied by the capstans on the Carnarvon side, which were signalled to for the purpose; but the strain thrown on the 12-inch guide-line to save the tube from fouling on the Britannia Rock snapped it asunder. It was afterwards found not to have been a sound line.

The radius-chain and two other ropes still remained, and were sufficient to prevent the tube from slueing round. Had these lines failed, the position of the tube would have been critical, and Mr. Whitting, who was in command on the pontoons, ordered his men to stand by their anchors.

As the Carnarvon ropes came into action, the tube was drawn against the butt on the Carnarvon shore, the pontoons fitting accurately in the excavation prepared for them on the beach. As the Britannia end came opposite the recess, it was found that the tube was not floating quite perpendicular, and could not be drawn into the tower, but became fixed between the piers of the recess. A capstan on the Britannia Rock was set in action to clear the tube from the masonry, but carried away its 12-inch line. The only course was, to open the valves at one end of the pontoons, when the tube immediately righted itself by their immersion, and glided easily into the tower, and a salute of 68-pounders announced the completion of the operation.

About 650 men were employed; 386 of them were sailors, most of whom were engaged temporarily from Liverpool for the purpose. The drifting away of the pontoons was managed very skilfully. Some water was admitted into them, care being taken not to sink the iron pontoons. They floated away, lashed together, and with the assistance of a steamer that was in attendance, and of the powerful anchors with which they were supplied, they were secured in the vacant excavations beneath the tubes.

The accompanying sketch gives the immersion of the pontoons and other data connected with the operation. It represents a section of one of the pontoons, with its 3 feet thickness of packing bearing against the bottom of the tube just at the moment of its lifting off the piers, or at the time of starting. The datum for the levels being the plinth of the Britannia Tower, which represents 25 feet on the local tide-guage employed.



Some useful practical facts were gathered from these operations. The use of chain-cable for guide-lines was found impracticable on account of the impossibility of buoying it and keeping it clear of the rocks, or hauling it taut. The speed attained by crabs with messengers was found insufficient for hauling in the slack, so that at Conway the chain bellied between the pontoons and their final position, and seriously interfered with the operations.

The necessity for fastening down the capstans, to keep them from being dragged out of the platforms when palled, was manifest with the first tube at the Straits, and was subsequently attended to.

The curve of the shaft of a capstan was found to be a point of great importance in surging.

The difficulty of taking up lines from boats or buoys during the progress of the tube, which were found very unmanageable in such a current, led to the successful use of the messengers as described.

The cable-stoppers acted perfectly; a similar apparatus appears to have been used by Telford, and is described by Mr. Provis in his "Description of the Menai Bridge."

And lastly, it was found that no dependence could be placed upon large untarred lines unless they are perfectly new, two 12-inch lines having been broken in the last operation described. The tarred ropes did not appear to have been damaged by laying by, but the white hemp ropes when once wetted were found to retain moisture in their interior with great obstinacy, and although carefully dried in the sun they became mildewed internally, and so much weakened as to be unfit for use in the subsequent floatings. In floating the two last tubes Manilla ropes were extensively employed, and, from their lightness and buoyancy in the water, and their durability and strength, were much preferred to the hempen ropes.

The Raising of the Tubes.

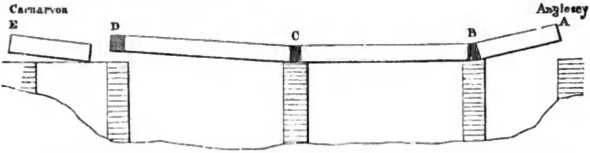
In twelve days after the floating was completed, which were spent in building up the masonry of the recesses and in the adjustment of the presses, the raising of the tube was commenced. During this period, and also until the tube attained an elevation of 60 feet, a steam-tug was engaged to tow vessels through the Anglesey Channel. In spite of this precaution a few vessels were drifted against the tube, but escaped with little damage, being hauled off by the capstans, which were always in readiness on either shore.

The tube was raised regularly 6 feet a-day without intermission, and without any incident beyond the occasional leakage of a joint. It thus attained its final elevation on the 7th January, 1850. The whole time occupied in raising it being only sixteen days, and the time actually employed in lifting about twelve hours.

The Junction of the Tubes.

The junctions now proceeded night and day. A sharp frost occurred on the 16th which froze the water in the pipes and presses, lifting one of the rams, with the cross-head and chains attached, through a space of 1¼ inch; thin laminæ of ice oozed out between the collar and the ram; and the safety-valve in the feed-pipe, with the weight on the lever, was raised a quarter of an inch. Some apprehension was felt that the presses might be damaged by the strain; but on subsequently using them this was not found to be the case,—fires were afterwards kept constantly beneath them.

The bed-plates were inserted beneath the suspended tube as before, and the Britannia end was now lowered on to its permanent bed. The position of the tubes was then as shewn in the following sketch:—



The junction-piece marked B had been constructed on the platform on which the tube A B was resting, and launched into the tower. The construction of A B was then finished, and the junction with B C completed, the extremity A being raised 14½ inches above its permanent bed.

The tube A B was then lowered by removing the timber blocks which supported it, and this had the effect of raising the centre of the large tube nearly 2 inches (1·89).

Secondly, the junction at C was completed in the Britannia Tower. The junction-piece D was then united to the tube C D, its end being raised 31½ inches above its permanent bed. The extremity D was then lowered by means of the hydraulic press inducing a strain over the Britannia Tower at C, and thus raising the centre of the tube C B through a further space of 1·57 inches, while its own centre was similarly raised 2·35 inches, the small tube A B having its deflection slightly increased.

As soon as the extremity D was lowered, the small tube E was united, its extremity E being also raised 14½ inches above its permanent bed. This tube was then lowered by removal of the platform on which it was supported, and its descent had the effect of raising the centre of the tube D C through a further space of 1·34 inches. The large tube D C was, therefore, raised 3·69 inches, and the other large tube C B was similarly raised 3·46 inches. But the last operation, while it raised the centre of D C 1·34 had the effect of lowering the other large tube C B ·32 inch; and, again, this downward motion of the large tube had a perceptible effect in raising the adjacent small tube A B. In this manner the whole tube from A to E became a continuous beam; the strains everywhere being nearly the same as though it had been constructed in one length and placed complete in its place.

The manner in which the amount of tilt to be given to each tube was practically determined will be explained in a subsequent chapter.

The result was most satisfactory, and the whole of the additional strength calculated upon was undoubtedly obtained.

The press was most severely tested in raising the extremity D, with its heavy junction-piece of 170 tons attached to it, and after it was united in the centre tower at C. This operation was requisite for the removal of the packing, and for preparing the permanent bed on which the tube reposes; during this operation the tube was suspended by the chains, and lowered gradually by the press. Mr. Stephenson superintended this interesting operation, which took place on the 6th February, and was the completion of all that was difficult in the first, or up-line, of the Britannia Bridge.

The junction with the small tube E was completed by the

4th of March, and that tube was lowered into its place; the permanent way in the meantime having been laid through the tube; and on Tuesday the 5th Mr. Stephenson, accompanied by Mr. Bidder, Mr. Lee, Mr. Trevethick, Mr. Appold, the Author, and his brother, first passed through the completed bridge, with three locomotives. Subsequently, during the same day, an enormous train, 945 feet in length, consisting of three engines and forty-five coal-waggons, and carriages containing 700 persons, and weighing altogether 503 tons, passed through the tube to Holyhead. The last rivet was at the same time formally put into the tube by Mr. Stephenson and Mr. Mare the contractor.

The deflection with 200 tons of coal in a train occupying 334 feet in one of the large tubes was found to be only ·4 of an inch.

The following remarks made by Mr. Stephenson on the above occasion, are thus recorded in the "Carnarvon Herald" of the 9th of March:—

"He came forward, he said, under a deep feeling of duty—a duty arising out of that sense of gratitude which was natural to every honourable mind on being made the recipient and depository of an important trust. He was about to propose the prosperity and health of the Directors of that Railway Company whose confidence in him had given birth to the proud triumph of the day. It was to him certainly a triumph, and a proud one, to have been able to prove to the most sceptical the possibility of that safe transit over the Menai by means of a tubular beam, which at first sight had appeared to be altogether impracticable. But, in exact proportion as he felt the importance of the triumph, did he feel a grateful consciousness towards those whose confidence and trust had enabled him to achieve it. No one could have more occasion than he had to feel grateful to the Directors for their confiding trust in him, for the completion of the undertaking was ever since its first commencement, daily and hourly, dependent on the unbroken continuity of their confidence. Had they ceased to confide, his project would have been inevitably blighted. Yet he was sometimes surprised himself at the unwavering trust which had been reposed in him, especially when the peculiar, the gigantic, and the unprecedented nature of the undertaking presented itself to the mind. To throw an iron tube over the Menai, of such solidity and strength as to ensure safe transit to the utmost extent of any possible contingent traffic, was no small undertaking; and well did he remember being startled at the magnitude of the idea when it first presented itself to his contemplation. He had witnessed without surprise, and consequently without annoyance, similar evidences of feeling in the minds of other men. It was, in fact, difficult to reduce an idea involving the contemplation and due arrangement of physical elements so stupendous without some feeling allied to awe or to dismay. When, however, the conception had become reduced to figures, calculations, and the minute consideration of all its details, he found it to be perfectly practicable and perfectly safe. The occurrences of the present day had proved this: how then could he be otherwise than grateful towards the Company who had unhesitatingly left to him the direction of the undertaking and the full completion of the plan? The scheme had not been perfected all at once, but had been the result of many combined considerations; the difficulties and details of which would shortly be made known to the world in a work which was being prepared by his friend Mr. Edwin Clark. The public would then be better able to appreciate the real difficulties that had been overcome. He felt it almost impossible to express the deep feeling of gratitude due from him to the Company for the vast trust they had reposed in him. He trusted that the event of this day would be the precursor of great future good; and would lead to a closer and more intimate intercourse between the two islands that would ensure the pacification and happiness of Ireland. Nothing could more deeply touch the feelings of the considerate and the humane than the present condition of that unhappy country; and for him to be instrumental to a measure, calculated to induce such important results, was a source of the most intense gratification; and he felt assured that there were none of those who co-operated with him, and might be termed his staff, that did not participate in the same feeling of joy and pride. Notwithstanding the national importance of the undertaking, he regretted to state that, in some other points of view, a cloud had hovered over it; but he was now glad to recognise the commencement of a more hopeful and brightening prospect to the financial interests of the Railway Company. The bridge which they had that day traversed had been built upon the grave of prejudices that ought to be altogether buried; and not stalk about in noon-day, in the face of a project that was in effect completed. Some errors, however, were difficult to remove. There was a class of men who erred from ignorance solely; and another whose errors arose simply from prejudice; another class combined both ignorance and prejudice in their mistakes, and comprised individuals who, to the worst features of ignorance and error, superadded malignity of motive and of will. The true and accurate calculation of all the conditions and elements essential to the safety of the bridge had been a source not only of mental but of bodily toil; including, as it did, a combination of abstract thought and well-considered experiment, adequate to the magnitude of the project. It had occupied himself, and those who shared in his toils, for a considerable period. And what could be said of those men who, without study, without toil, without knowledge, without having submitted their notions to the test of experiment, came forward to shake the confidence of the public by raising a cry of danger where all was safe and durable as the material of the bridge itself? He did not mean to be personal in his allusions; and when he glanced around him, and saw the number and respectability of those who had risked themselves with him that morning, he felt that the most unqualified contradiction had been given to the false cry adverted to. Persons capable of appreciating the nature of such calculations as were essentially preliminary to the formation of such a bridge, would know that such calculations were not visionary; and what was the result? Why! that the bridge would sustain, and sustain safely, more than seven such trains as had that day passed through it, were they piled one upon another; and that a weight of three thousand tons might safely press upon any part of the floor of the tube, or be suspended from its centre. In fact, there was no portion of the railroad so adequate to its work as was this tube. Accompanied by three locomotives, and a heavy load, nearly one thousand individuals had volunteered to accompany him that day: the fact was to him a source of happiness and pride."

On the 15th of March the bridge was examined by Capt.

Simmons, the Government Inspector, and opened for public traffic on the 18th of March, 1850. The test employed by Capt. Simmons consisted of 27 coal-waggons, weighing 248 tons, and filling one large tube to within 38 feet from each extremity.

The morning was bright and warm, and the deflection of the tube was constantly varying from the effect of the sun. On placing this train in the Anglesey large tube, it produced a deflection of ·775 inch; and the same weight produced a deflection of ·65 inch in the Carnarvon Tube. The load was left in the Anglesey Tube one hour, and the decrease of deflection caused by its removal was ·605 inch. The mean deflection of the large tubes from this weight is therefore ·676 inch. On removal of the load the deflection was found to be rather less than previous to its introduction.

The placing of the load in one large tube had the effect of raising the centre of the other large tube ·19 inch, and the centre of the neighbouring small tube was similarly raised ·109.

The maximum deflection of the small tube during the passage of the above train, with one engine at each end, was ·141 inch. The maximum deflection of the same small tube, from the passage of a single engine and tender weighing 30 tons, was ·109 inch.

The train with two engines was run through the bridge at the usual rate at which such trains travel. The tremor or molecular shiver was such as to prevent the accurate determination of the deflection, but it was about the same as with the same weight at rest.

The steam that collected in the tube rapidly condensed on the cold side of the tube, which was covered with dew; but on the warm or sunny side no condensation took place. The light on the surface of the steam that rolled along the bottom had a pleasing effect. The spectator appeared to be walking over a stratum of beautiful clouds, with all the colours and outlines of the ordinary cumulus. The steam oozed externally through every hole or open joint in the sides, as though under pressure from within, and the appearance of the sunny landscape at the extremities, through the coloured medium occasioned by the smoke, was extremely beautiful.

An effectual arrangement was used to prevent the possibility of a collision between two trains while the single line of tube only was opened. A man was constantly stationed there, whose duty it was to pass through personally with every train, and as this individual did not possess the power of ubiquity, it was impossible for two trains to be in the tube at the same time.

Floating of the Third Tube.

The floating of this tube took place on the 10th of June, 1850. It was constructed in the position marked No. 4, Plate I., and was more remote from the towers than any other. It had to be transported 2200 feet, or very nearly half a mile. The journey was accomplished in two stages. The first movement was made on the 23rd of May, and consisted in swinging round the tube on its pontoons from the position in which it was constructed into the next excavation, marked No. 3 in the Plate. It was thus brought into the same position that the first tube had been floated from, and the arrangements for the final movement were exactly similar. The operation was very simple. A strong bowsprit, or outrigger, was fixed to the end of the tube, its extremity being fashioned like the boom of a vessel; this bowsprit revolved round an upright mast, which was erected exactly half-way between the two docks, and the tube was swung round upon this mast as a centre from the position No. 4 into No. 3, one end of the tube being only moved a few yards, while the opposite extremity swept round in a circuit of one-eighth of a mile; and its higher end, which had previously been turned towards Carnarvon, was thus brought to the Bangor end, in a proper position for floating it between the towers. A very low tide was used, and the operation occupied exactly half-an-hour. It was a fine calm summer's evening, and as the tube glided round with a rapid but imperceptible motion, the landscape had the appearance of a vast panorama sailing majestically round, while to spectators on shore the tube itself had an equally imposing effect, where, in its midway career, it appeared almost to block up the passage of the Straits.

As before observed, the arrangements for the final movement were almost exactly the same as those used in floating the first tube, and as figured in Plate II. The guide-lines were laid out as before; but to avoid the difficulty of taking up the remaining lines from fixed moorings, messengers led from the pontoons to each capstan, so that, as the tube advanced, the lines were hauled in by the men at the capstans without the delay of waiting to pick them up on the road. The morning was extremely fine, and every line was new and well laid out. The arrangements were altogether more perfect than ever, and there appeared no reason to apprehend the least difficulty. The operation, however, turned out by far the most hazardous that had occurred, and the safety of the tube was at one moment a matter of considerable doubt.

A series of misadventures occurred, which began at the moment of starting, for on hauling the tube out into the stream it was drawn by the current in contact with a portion of the platform at the eastern extremity, and ten minutes were lost in cutting away the obstruction. This loss of time induced more haste than usual in the remainder of the operation, while the tide obtained an unexpected height and velocity, and was assisted by a considerable breeze from the west. The tube glided down the guide-lines on the current with a velocity of rather more than 1 foot per second, which was well regulated by the cable stoppers. It was, however, found impracticable to haul in the messengers attached to the ropes from capstans H and C, and it soon became evident that the operation must be performed without the assistance of these important lines. The line from capstan C bellied down the current on the Carnarvon channel, and the line from capstan H, though a light Manilla rope, became foul among the rocks.

The slueing round into positions 6, 7, and 8, had to be performed without any line from the Britannia end of the tube. This induced some precipitancy in striking the butt placed on the western side of the Anglesey Tower. The blow, not being checked from capstan H, was very severe, and the tube rested on the butt at too great a distance from the tower. The outer guide-line was thrown off, and the tube swung round in the tide, which was now very violent, with unchecked velocity, and the only lines available for regulating the speed were the inner guide-line and the temporary hauling-out line, which had fortunately been lengthened during the journey, and was retained, although intended to be cast off. Sixteen men on the cable-stopper of the inner guide-line were scarcely able to clamp it, and the rope, which was of remarkable strength, was much damaged by the friction. The hauling-out line was also severely strained, and the tube struck the butt beneath the Britannia Tower with a fearful crash, throwing down several persons on the pontoons. The greatest anxiety was felt lest the butt should be carried away, but it yielded to the concussion; and the tube, after deflecting laterally several inches from the blow, rebounded from the timbers. The Anglesey end not being in its proper position, the tube struck only the outer portion of the butt, and thus the blow came almost entirely on a single upright balk, which was, however, well strutted from behind. To add to the difficulties of this position the current forced the tube into the timber; and as the tide was rapidly rising, the piles began to be drawn out of the ground, in which case the tube must have passed by the tower and have been irretrievably lost. The timber was, however, rapidly cut away by the carpenters, and the strain relieved by the capstans on the rock, which were now brought into action with fresh ropes, and the operation was successfully completed.

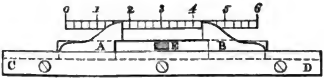
Thus has some unforeseen misadventure characterised each of these vast operations. The best-planned schemes have been found liable to derangement and difficulty.

Although the tubes offer so effectual a resistance to deflection by heavy weights and gales of wind, they are nevertheless extremely sensitive to changes of temperature, so much so that half-an-hour's sunshine has a much greater effect than is produced by the heaviest trains, or the most violent storm; they are, in fact, in a state of perpetual motion, and after three months' close observation, during which their motions were recorded by self-registering instruments, were never observed to remain at rest for a single hour.

These motions are of considerable amount, and of a very interesting character; the most obvious are the direct changes in length of the tubes, which, as before explained, are fixed only in the centre tower, and the two halves being supported on rollers in the other towers, expand and contract freely with changes of temperature.

A simple instrument at each extremity permanently records the maximum and minimum temperature of the atmosphere in the shade of the tube, and the consequent changes of its length or motion on the rollers.

This instrument consists of a fixed iron bar, E, leaded into the masonry of the abutments, and projecting internally through a horizontal groove in the side-plates. Two cheeks, A B, sliding in a groove in the bar C D, which is attached to



the tube internally, are first brought into contact, and as the tube expands or contracts, the cheeks are separated to the right or left, the amount of separation being measured on a scale above them.

Two self-registering thermometers record the temperature, and the whole is protected by a mahogany case with a plate-glass in front, secured under lock and key. Thus the maximum and minimum temperature and the maximum amount of motion, since the adjustment of the instruments, may at all times be readily observed, each instrument giving the motion of one half of the whole bridge.

The instruments were adjusted at the beginning of March, the temperature of the tube being 32°, and the registers marking $2\frac{1}{2}$ inches. From that period to the present time (July) the temperature of the atmosphere within the tube has varied from 26° to 76°, and the maximum motion of the tube has been $6\frac{3}{8}$ inches in the entire length, or $3\frac{3}{16}$ths at each extremity.

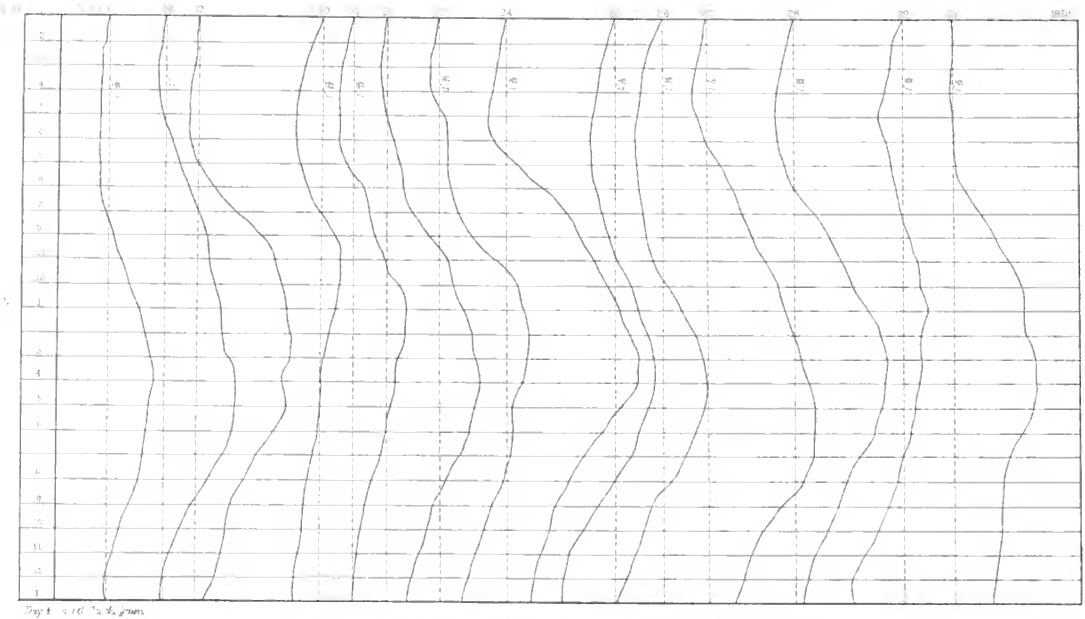
The temperature of the tube, however, differs widely from that of the atmosphere in the interior, for the top during hot sunshine has been observed to reach 120°, and even considerably more; and, on the other hand, a thermometer on the surface of the snow on the tube has registered as low as 16°.

By observations, however, made at midnight and at seasons when the temperature remained constant, tolerably correct comparisons of the actual temperature of the tubes and their corresponding lengths have been obtained. An increase of temperature of 26°, viz., from 32° to 58°, gives an

To face P. 715

BRITANNIA BRIDGE

Diurnal Expansion of Half the Bridge



The figures under the dotted lines give the increase beyond the length at temperature 32° Fahrenheit increase of length of $3\frac{1}{4}$ inches in the whole bridge, which is 1510 feet $1\frac{1}{2}$ inch long at 32°; the variations in the two halves are at all times perfectly uniform. The expansion is thus $\frac{1}{8}$ inch for each degree, or $\frac{1}{145000}$th part of the whole length.

The daily expansion and contraction of the tube varies from $\frac{1}{2}$ an inch to 3 inches, usually attaining its maximum and minimum about three o'clock in the afternoon and morning. The observations are taken by a self-acting clock-work arrangement, which slowly elevates a board in a vertical plane, while the motions of the tube are delineated upon it by an arm carrying a pencil, which is fixed to the tube. The accompanying Plate gives the curves traced by the pencil with this machine. The following table will also give an idea of the daily extent of the variations; the expansion is that of the whole bridge.

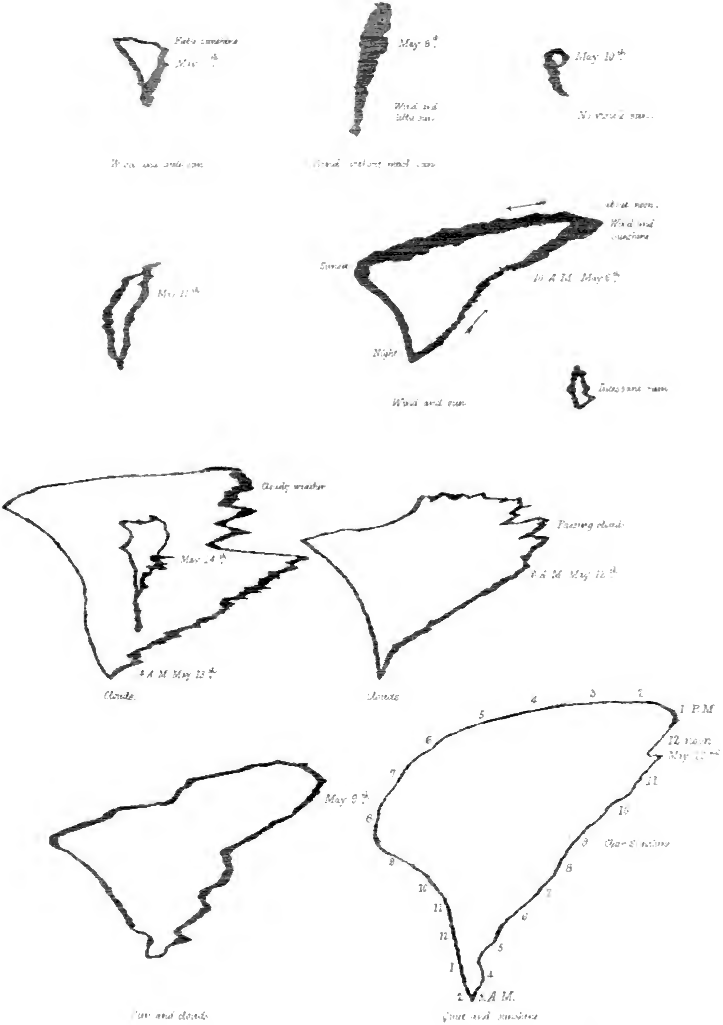
	Expansion.	Highest Temp^e.	Time.	Lowest Temp^e.	Time.	Remarks.
1850. June 17	$\frac{13}{16}$	58	5 P.M.	51	5 A.M.	Cold and cloudy; no sun.
18	$1\frac{10}{16}$	61	5 P.M.	54	6 A.M.	Cold and cloudy; little sun.
19	$1\frac{8}{16}$	61	1 P.M.	54	6 A.M.	Cold and cloudy; little sun.
21	$\frac{12}{16}$	62	1 P.M.	58	3 A.M.	Cold S.E. wind, and cloudy.
22	$1\frac{11}{16}$	$65\frac{1}{2}$	3 P.M.	60	3 A.M.	Cloudy.
23	$1\frac{5}{16}$	$66\frac{1}{2}$	2 30 P.M.	61	5 A.M.	Cloudy.
24	$2\frac{3}{16}$	73	1 P.M.	63	7 A.M.	A fine warm sunny day.
25	$1\frac{12}{16}$	66	1 P.M.	57	5 A.M.	Cold N.E. wind, and cloudy.
26	$1\frac{10}{16}$	62	3 P.M.	55	4 A.M.	Cold N.E. wind; little sun.
27	$1\frac{10}{16}$	66	5 P.M.	55	3 A.M.	Cloudy, with some sun.
28	$1\frac{12}{16}$	65	4 P.M.	56	6 A.M.	Clouds and sun; W. wind.
29	$1\frac{2}{16}$	61	12 NOON.	55	3 A.M.	Very cloudy and cold; N.W. wind.
30	$\frac{14}{16}$	65	3 P.M.	57	9 A.M.	Very wet and cloudy. the therm. standing for 8 hours at 58°.

But the most interesting effect is that produced by the sun shining on one side of the tube, or on the top, while the opposite side and the bottom remain shaded and comparatively cool. The heated portions of the tube expand, and thereby warp or bend the tube towards the heated side, the motion being sometimes as much as 2½ inches vertically, and 2½ inches laterally.

While the tubes were supported on the temporary piers on the beach these motions were easily observed. An arm carrying a pencil was fixed on the south side of the tube, No. 2 in plan, at the centre, and a board was fixed on a post independent of the tube, and at right angles to it; the pencil was pressed against the board by a spring, and the rise and fall, and the lateral motions of the tube, were consequently traced on the board. In this way a very interesting diagram was taken daily; fac-similes of the figures traced on several consecutive days in the month of May are given on the accompanying Plate. The lower point of each figure is the starting point, or normal position of the tube, to which the pencil always accurately returns during the night. As soon as the sun rises in the morning it starts towards the right hand, rising obliquely, the top and one side of the tube becoming warmed, and the bottom and opposite side remaining unaffected. It continues thus to rise till one o'clock, when the sun, having ceased to shine on the southern side, begins to warm the northern side, the top still retaining its high temperature; the tube thus acquires a nearly horizontal motion towards the left hand, the slight descent in the line indicating the diminished effect of the sun on the top, as it gradually sinks. The greatest deflection to the left hand is not attained until sunset, after which the tube rapidly descends in a uniformly curved line to its resting point; in the summer time this point is hardly attained before the rising sun compels it to commence its journey anew.

When the sun is frequently obscured by passing clouds

DAILY HORIZONTAL & VERTICAL MOTION OF THE TUBES.



Day & Son lith to the Queen

very curious diagrams are obtained. During the absence of the sun the tube begins to cool rapidly, and to return to its normal position; every passing cloud is thus beautifully recorded, as in the accompanying Plate.

Even in the dullest and most rainy weather, when the sun is totally invisible, the tube rises slightly, shewing that heat, as well as light, is radiated through the clouds: an instance of this is seen in the Plate. The average daily motion during the month of June was $1\frac{3}{4}$ inch horizontally and $1\frac{1}{2}$ inch vertically. When the sun shines only in the middle of the day the motion is all vertical; but when a dull and rainy day is succeeded by a bright evening, the horizontal motion becomes considerable, with very little rise; the smallest rise recorded is $\frac{3}{8}$ths of an inch. On very hot sunny days the lateral motion has been as much as 3 inches, and the rise and fall 2 inches and $\frac{3}{10}$ths.

This motion will appear very considerable when it is remembered that after the tubes are connected together the deflection produced by a heavy train is only $\frac{3}{10}$ths of an inch, and that a violent gale does not bend them more than $\frac{1}{4}$ of an inch.

In a similar manner the horizontal oscillations occasioned by the wind are registered, making a more or less thick line, as in the diagrams of May. Even the precise hour of the day when the wind was strongest may be ascertained; and no meteorologist has preserved a better diary of the weather than exists in these fantastic figures, if properly interpreted.

The effect of pressure against the side of the tube is very striking; a single person, by pushing against the tube, can bend them to an extent which is quite visible to the eye; and ten men, by acting in unison, and keeping time with the vibrations, can easily produce an oscillation of $1\frac{1}{4}$ inch, the tube making 67 double vibrations per minute. After working about $2\frac{1}{2}$ minutes the tube offers a stubborn resistance to any further deflection from the friction on the bearings, and it is evident that ten men could never produce a much greater oscillation.

The effect of the wind on the tubes during violent storms has been very much dreaded by many persons; it was feared that the pulsations of the gale might become isochronous with the vibrations of the tube, and thus create an amount of oscillation that would be injurious. When it is, remembered, however, that the tube vibrates naturally sixty-seven times per minute, while gusts of wind always last many seconds, all apprehension of danger from this cause vanishes. The first line of tubes was erected during the winter of 1849–50, and during this interval many gales of unusual violence occurred, so as to occasion frequent interruptions to the work. The storm of the 14th of January was universally noticed from the damage it occasioned both on shore and at sea, and its effects have already been noticed. It was undoubtedly the most violent that had occurred for twenty years. The Carnarvon Tube was at this time at its full elevation, although partially suspended in the chains, and was totally unconnected with the other tubes; it presented a full broadside to the storm, and experienced, therefore, the utmost fury of the gale. The storm had partially abated at daylight, at which time the oscillations were about $\frac{3}{4}$ths of an inch, and never exceeded 1 inch; they were quite irregular in their periods, and appeared greatest during a lull, or immediately after the abrupt cessation of a violent gust, when they also became for a short time regular. It was at this time quite impossible for any one to walk across the tube.

Thus the heaviest gales do not produce so much motion as ten men, although it must be observed that even when acting simultaneously they are not able to vibrate the tube $\frac{1}{8}$th of an inch when their efforts are not timed with the oscillations.

The foregoing effects, both of the sun and wind, have reference to the tubes before they are united together in the towers; after being thus connected together these effects are materially diminished—the heaviest gales of wind do not vibrate them more $\frac{1}{4}$ of an inch; and the sun, instead of bending them 2 or 3 inches, does not appear to move them more than $\frac{2}{8}$ or $\frac{3}{8}$ths of an inch; and when the two lines of tubes are further connected together, side by side, these motions will be almost annihilated, and all apprehension of damage from wind or weather ceases.

The only other motions of interest are those produced by the passage of the trains. It has already been shewn that the heavy trains, purposely introduced by Captain Simmons to test the tube, produced a deflection of rather less than $\frac{3}{4}$ths of an inch, while at the same time the tubes have been raised 4 inches by their connexion over the towers; it would, therefore, require five or six such trains to bring the tubes into the same strain as when they were resting singly on the piers. The ordinary trains which pass through the tubes have the effect of deflecting them from 2 to $2\frac{1}{2}$, or sometimes 3-tenths of an inch, while at the same time the neighbouring tubes are raised about a third of that amount; and the moment the train enters one of the small tubes, the effect is perceptible, even on the more distant of the large tubes.

The great tremor occasioned by the train prevents the deflections being read by an ordinary spirit-level. Mr. Stephenson has, therefore, erected an elegant contrivance by which these effects are indicated with great precision. It consists of a pipe containing water, which is laid along the lower cells, one end rising up within the tube at the centre, and the other end against the fixed stone-work of the abutment. Both extremities are furnished with glass tubes and graduated scales, by which the relative levels of the water are easily ascertained. In this simple state, however, it has several disadvantages; the slightest leakage or evaporation, or the ordinary thermometric expansion of the water, would perpetually derange the level, while only half the actual deflection of the tube is registered at each end of the pipe; all these disadvantages are obviated by the addition of a larger reservoir of water in the interior of the tube, which is covered with oil, and placed beside the graduated tube. This larger area causes the whole deflection to be shewn at the abutment extremity, and prevents any slight loss from evaporation becoming visible, — the instrument thus becomes a permanent record of the present position of the tube, and affords a ready means of observing any temporary or permanent deflections that may take place.

Some of the acoustic effects produced by the bridge are interesting. The report of a pistol fired beneath the tubes is repeated three or four times. In this particular, however, they are far surpassed by the large brick arches constructed by Mr. Brunel over the Thames at Maidenhead, under which the echo of a pistol is repeated from twelve to twenty times. The rapid repetition of echoes from each of the T-irons on the side of the tube gives rise to a shrill, whirring musical note. When any violent noise is produced on the adjacent shore the note is the same, whether produced by the blows of the riveters or the report of cannon, and corresponds to the low D on a concert-flute. The distance between the T-irons is 2 feet. If the same note be sounded by a flute close beside one of the tubes, it is repeated in a perfectly soft and musical tone, which lasts many seconds. The report of a pistol produces the same effect much more powerfully.

The effect of music in the interior is very striking, and a concert which was given in one of the tubes to the workmen was very effective. The floor was boarded, and the interior being illuminated by several thousands of candles, had a most imposing and gorgeous appearance.

The cells of the top and bottom form excellent speaking tubes, and conversation may be carried on through them even in a faint whisper. By elevating the voice persons may converse through the entire length of the bridge, a distance of more than 500 yards. If one end of the cells be closed they return a powerful echo; but although a whisper is thus distinctly repeated, the loudest whistle does not appear capable of returning any echo.

The effect produced by these large masses of iron on the magnetic needle is not so singular as might perhaps be expected. If a compass be held near any part of the bottom cells the south pole is attracted, and if held near the top cells the north pole is attracted. The same effects prevail at all parts of the tubes, whether at the centre or the ends, although their position is only about 10° west of the magnetic meridian. They possessed the same properties while resting on the piers on the beach below.

The tubes are painted with light buff colour, both externally and internally. Two coats of red lead paint were first applied. The plates, after being delivered to the contractors, were unfortunately suffered to remain exposed to the weather for many months, and some of them even became wetted by high tides; they became, in consequence, much rusted, and great expense and difficulty was afterwards incurred in scraping and cleaning them, and nearly the whole of the first coats of paint had to be removed, together with the rust. The floor of the tube in the interior is painted with a mixture of 9 gallons of coal-tar, 9 lbs. of slacked lime, and two quarts of spirit of turpentine. This mixture appears to form a very economical and durable black paint. A boarded pathway is formed through the tube, and sufficient light is admitted through a number of small, circular, glazed apertures in the sides to render the passage through the tubes safe and convenient. There is sufficient breadth within to allow persons to stand safely on either side while a train is passing. There is also sufficient room between the top of the tubes and the stonework of the towers to allow persons to pass across the top, and the interior of the Britannia Tower is fitted up into a paint-store for the permanent maintenance of the bridge; a door in the side of the tubes leads up to this shop and to the top of the tubes.

A suspended stage hangs across the tubes, and is capable of traversing their entire length on wheels; ready access is thus obtained to the sides and bottom for the purpose of cleaning and painting.

It is intended to roof the tubes with galvanised tinned iron, in a similar manner to those at Conway; and it is also intended to connect the tubes together in pairs by cross-struts, that they may offer a joint resistance to the wind.

The number of fatal accidents that have occurred during the construction of the bridge is fortunately small, when compared with the magnitude and duration of the work.

Although so vast an amount of material has been moved and elevated to so great a height, only one of these accidents has been occasioned by the breaking of tackle,—a fact which speaks well for the care of the workmen, and the strength and fitness of the machinery employed by the contractors. Five have been killed by accidentally falling from a height, one by the sliding of a balk of timber, another by the tottering over of a pile of stones, one by the fall of a plank, one by the slipping of the rope round a capstan while lowering the large hydraulic press, and one by being thrown from a rope-ladder at the time of the bursting of the press.

A neat and elegant stone monument has been erected by the stone-masons to the memory of their deceased companions. It stands in the little churchyard of Llanfairpwllgwyngyll, which is close to the foot of the bridge, on the Anglesey side.

During the construction of the bridge a considerable village was formed at the foot of the bridge on either side. A number of temporary wooden cottages were built by the Railway Company, the contractors, and shopkeepers. A surgeon, in the pay of the workmen, constantly resided upon the ground to attend in case of accidents; and a chaplain was provided by the Railway Company. A daily school was also established, and the village was well supplied with provisions, the prices of which became much enhanced by the increased demand.

A long and well-wooded strip of land, extending from the Britannia to the Menai Bridge, is included between the Railway and the Straits. This piece of land overlooks the Swelly Rocks, commanding very fine views of the two bridges and of the distant ocean, and it is in contemplation to form serpentine carriage drives through it, and to erect a number of villas upon it: very beautiful designs with this object have been furnished by Joseph Paxton, Esq.

It has also been proposed that a railway station and hotel should be erected on the same ground, about midway between the two bridges, at a point from which a junction railway to Carnarvon will branch off.

With such advantages, backed by the vicinity of the Snowdon mountains and the sea, this beautiful locality cannot fail to become a highly popular place of summer resort.

CHRONOLOGICAL SUMMARY.

BRITANNIA BRIDGE.

1840.		Line surveyed by the late George Stephenson.
1844,	July 4.	Chester and Holyhead Railway incorporated—railway works commenced.
1845,	June 30.	Bill passed sanctioning the construction of the Britannia Bridge—received the Royal Assent.
	July.	Preliminary experiments commenced.
1846,	April 13.	First workmen engaged on the bridge.
	Sept. 21.	First stone laid, Britannia Tower.
1847,	June 13.	First vessel with iron arrived at the Straits.
	Aug. 10.	First rivet inserted in the Britannia Tube by Mr. Edwin Clark.
1849,	Feb. 22.	Carnarvon and Anglesey Towers completed.
	April.	Pontoons brought from Conway to Britannia.
	May 4.	First Britannia Tube completed, and platform cut away.
	June 20.	First tube floated.
	„ 22.	Last stone on the Britannia Tower laid by Mr. Stephenson.
	Nov. 9.	First tube deposited on its permanent bed.
	Dec. 4.	Second tube floated.
1850,	Feb. 7.	Second tube deposited on its permanent bed.
	March 3.	Carnarvon small tube lowered.
	„ 5.	First engine passed through the tubes, and last rivet inserted by Mr. Robert Stephenson.
	„ 18.	Single line opened for public traffic.
	June 10.	Third tube floated.
	July 11.	Third tube deposited on its permanent bed.
	„ 25.	Last tube floated.

SECTION VIII.

STRENGTH AND DEFLECTION OF THE TUBES.

CHAPTER I.

COMPUTATION OF THE STRENGTH AND DEFLECTION OF TUBES FIRST PROPOSED FOR CONWAY.

In the month of December 1846, drawings of the tube then proposed for the Conway Bridge were furnished to Mr. Hodgkinson by Mr. Robert Stephenson to ascertain, theoretically, the strength of such a tube, and the probable amount of its deflection.

The tube then proposed had two sets of cells at the top, which was composed of three horizontal plates and ten vertical ones, the thickness being half an inch. The whole width was 14 feet 1 inch, and the depth of the vertical plates 3 feet.

The top sectional area included also eighty angle-irons; the section of each being 2·794 square inches, or 2·5, deducting rivet-holes.

The total area of the top section was thus 633·5 square inches.

The top was composed of three horizontal plates and seven vertical plates, all half-inch thick; the depth of the vertical plates was 1 foot 9 inches. There were thirty-two angle-irons; thus the whole sectional area of the bottom was 407 square inches.

The distance of the neutral axis from the bottom was determined to be 101·23 inches, and the strain from the weight of the tube itself, and its ultimate strength, were determined on these data.

The elaborate calculations of the strength and deflection of this tube, as made by Mr. Hodgkinson, will be found in the Report of the Commissioners before referred to.

In March 1847, the form of the tube for the Conway Bridge was considerably modified, and the strength was again computed by Mr. Hodgkinson.

The section of this tube is nearly the same as that of the completed bridge.

First, the Situation of the Neutral Line.

In this tube the cellular top is composed of two horizontal plates and nine vertical ones, including those on the sides opposite to the cells; and the thickness of the plates is $\frac{3}{4}$-inch each.

The whole width is 14 feet 1 inch; whence 14 feet 1 inch × 2 = 28 feet 2 inches.

The depth of the vertical plates is 1 foot 9 inches; therefore 1 foot 9 inches × 9 = 15 feet 9 inches, the length of the vertical plates.

The whole length of the plates is, therefore, 28 feet 2 inches + 15 feet 9 inches = 43 feet 11 inches = 527 inches, and the area of their section = $527 \times \frac{3}{4} = 395 \cdot 25$ square inches, the whole area of the plates composing the top of the tube. These cells contain in their corners in addition forty angle-irons, the section of each of which is 4 inches; whence, $40 \times 4 = 160$ square inches, the area of their sections. There are, likewise, sixteen longitudinal strips to cover the joints, the area of section of which is $16 \times 9 \times \frac{1}{2} = 72$ square inches.

We have, therefore, $395 \cdot 25 + 160 + 72 = 627 \cdot 25$ square inches = the whole area of section of the cells, which we will call A. The centre of gravity of this mass is very nearly in the middle.

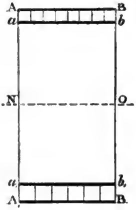
The cellular bottom of the tube, as proposed, is composed of two horizontal plates of 1 inch thick each, and seven vertical ones of ½-inch thick each.

The length of the horizontal plates is 14 feet 1 inch × 2 = 28 feet 2 inches = 338 inches, and their thickness being 1 inch, their area of section is 338 square inches.

The length of the vertical plates is 1 foot 9 inches × 7 = 12 feet 3 inches = 147 inches, and their thickness being ½-inch, 147 × ½ = 73·5 square inches. Whence, the area of the section of all the plates in these cells is 338 + 73·5 = 411·5 square inches.

In these cells there are likewise thirty-two angle-irons, the area of section of which is 32 × 2½ = 80 square inches. We have, therefore, 411·5 + 80 = 491·5 square inches in the section of the plates and angle-irons of the lower cells of the tube, and this area we will call $A_,$. The centre of gravity of this mass is in its middle.

Suppose the annexed diagram to represent a section of the tube in the middle, and N O to be the neutral line.



Let us then put,

A = the area of the section of the cellular top ($A\,b$) = 627·25 square inches;

$A_,$ = the area of the section of the bottom ($a_,\,B'$) = 491·5 square inches;

d = distance ($a\,a_,$) = 21 feet $6\frac{7}{8}$ inches = 258·875 inches;

c = half distance ($A\,a$) = $\frac{22{\cdot}5}{2}$ = 11·25 inches, the distance of centre of gravity of upper cells, from bottom of plate ($a\,b$);

$c_,$ = $\frac{23}{2}$ = 11·5 inches, the distance of centre of gravity of lower cells, from top of plate ($a_,\,b_,$);

t = thickness of side ($a\,a_,$), or ($b\,b_,$) = ½ inch;

x = ($N\,a$) the distance of the neutral line from the bottom of the top cells;

$x + c$ = distance of centre of gravity of A, from neutral line;

$d - x + c_, =$,, ,, $A_,$,,

$\frac{x}{2} =$,, ,, $2\,t\,x$,,

$\frac{d - x}{2} =$,, ,, $2\,(d - x)\,t$,, The last two equations refer to the side plates, between the top and bottom cells.

Therefore, $(x+c)\,A$ = moment of the area A with respect to the neutral line;

$(d-x+c_{,})\,A_{,}$ = „ „ $A_{,}$ „ „

$t\,x^2$ = „ „ $2\,t\,x$ „ „

$t\,(d-x)^2$ = „ „ $2\,t\,(d-x)$ „

Equating the moments, on the opposite sides of the neutral line, we have,

$$(x+c)\,A+t\,x^2=(d-x+c_{,})\,A_{,}+t\,(d-x)^2$$

whence,
$$x=\frac{(d+c_{,})\,A_{,}-c\,A+t\,d^2}{A+A_{,}+2\,d\,t}.$$

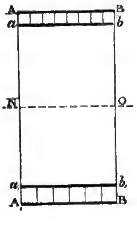
Inserting in this equation the numerical values, gives—

$$x=\frac{(258{\cdot}875+11{\cdot}5)\,491{\cdot}5-11{\cdot}25\times 627{\cdot}25+{\cdot}5\,(258{\cdot}875)^2}{627{\cdot}25+491{\cdot}5+2\times 258{\cdot}875\times{\cdot}5}=115{\cdot}66 \text{ inches.}$$

This computation has been made on the supposition that the angle-irons acted with their whole force, both of tension and compression, in the same manner as the plates; but it is probable that the angle-irons in the lower part of the tube would not act with their whole tensile force, as mentioned in the computation of the strength, according to the former supposition.

Secondly, to find the Strength of the proposed Tube.

To find the moment of the forces, and the weight borne by the tube, the same reasoning is used as in the investigations on that previously proposed.



The top and bottom of the present tube are of the same form as the lower part in the former one. The distance (N a), from the neutral line to the bottom of (a b), is 115·66 inches, and the distance (N $a_{,}$), from the neutral line to the top of ($a_{,}$ $b_{,}$) = 258·875 − 115·66 = 143·215 inches.

This position of the neutral line will be supposed to remain unchanged, notwithstanding any change of supposition with respect to the action of the angle-irons, since the effect of such a change would have very little influence on the strength.

We shall therefore assume—

$a = (\mathrm{N\,A}) = (\mathrm{N}\,a) + (a\,\mathrm{A}) = 115{\cdot}66 + 22{\cdot}5 = 138{\cdot}16$ inches, the distance from the neutral line to the top of the tube;

$a_{,} = (\mathrm{N\,A}_{,}) = (\mathrm{N}\,a_{,}) + (a_{,}\,\mathrm{A}_{,}) = 143{\cdot}215 + 23{\cdot} = 166{\cdot}215$ inches, the distance from the neutral line to the bottom of the tube;

$(\mathrm{A\,A}_{,})$ the whole depth $= 304{\cdot}375$ inches $= 25{\cdot}3646$ feet;

$b = 169$ inches, the whole external breadth;

$c = 22{\cdot}5$ „ the whole depth of the top cells;

$c_{,} = 23{\cdot}$ „ „ „ bottom cells;

$t = {\cdot}75$ „ the thickness of the plate $(\mathrm{A\,B})$, or of the plate $(a\,b)$;

$t_{,} = 1$ inch, the thickness of the plate $(\mathrm{A}_{,}\,\mathrm{B}_{,})$, or of the plate $(a_{,}\,b_{,})$;

$s = 1$ „ the thickness of the side plates $(a\,a_{,})$ and $(b\,b_{,})$ taken together;

$s' = 6{\cdot}75$ inches the thickness of the vertical plates between $(\mathrm{A\,B})$ and $(a\,b)$, including the sides opposite to them;

$s_{,} = 3{\cdot}5$ inches the thickness of the vertical plates between $(\mathrm{A}_{,}\,\mathrm{B}_{,})$ and $(a_{,}b_{,})$, including the sides opposite to them.

Now if f be the force exerted by the particles in a unit of section, and at a unit of distance from the neutral line, as before, we have, taking that unit as one inch—

$f a = f \times 138{\cdot}16$, the force of the particles in a unit of section at the top of $(\mathrm{A\,B})$;

$f\left(a - \frac{t}{2}\right) = f \times 137{\cdot}785$, the force of the particles in a unit of section at the centre of $(\mathrm{A\,B})$;

$f(a - t) = f \times 137{\cdot}41$, the force of the particles in a unit of section at the bottom of $(\mathrm{A\,B})$, to which the angle-irons are attached;

$f\Big((\mathrm{N}\,a) + t\Big) = f \times 116{\cdot}41$, the force of the particles in a unit of section at the top of $(a\,b)$, to which the angle-irons are attached;

$f\left((\mathrm{N}\,a) + \frac{t}{2}\right) = f \times 116{\cdot}035$, the force of the particles in a unit of section at the centre of $(a\,b)$;

$f \times (\mathrm{N}\,a) = f \times 115{\cdot}66$, the force of the particles in a unit of section at the bottom of $(a\,b)$.

In like manner—

$f \times 166\cdot215$ = force of the particles in a unit of section at the bottom of $(A_{,} B_{,})$;

$f \times 165\cdot715$ = force of the particles in a unit of section at the centre of $(A_{,} B_{,})$;

$f \times 165\cdot215$ = force of the particles in a unit of section at the top of $(A_{,} B_{,})$, to which the angle-irons are attached;

$f \times 143\cdot215$ = force of the particles in a unit of section at the top of $(a_{,} b_{,})$;

$f \times 143\cdot715$ = force of the particles in a unit of section at the centre of $(a_{,} b_{,})$;

$f \times 144\cdot215$ = force of the particles in a unit of section at the bottom of $(a_{,} b_{,})$, to which the angle-irons are attached.

We will first obtain the moments of the forces of the plates, and afterwards those of the angle-irons.

Moments of the Forces of the Plates.

To determine these, the same mode is adopted as in the previous previous calculation; the computation at full length will be found in the Report of the Commissioners, p. 164 *et seq.*

1st. To obtain the moments of the forces of the plates composing the sides $(a\,a_{,})$ and $(b\,b_{,})$, neglecting those of the cells. If we consider the sides (Na), (Ob), and $(Na_{,})$, $(Ob_{,})$, above and below the neutral line, as acting like rectangular masses, or joists bent transversely, the moments of their resistance will be as below:—

$$\frac{f \times 115\cdot66}{3} \times s\,(Na)^2 = \frac{sf \times 115\cdot66}{3} \times (115\cdot66)^2 = sf \times \frac{(115\cdot66)^3}{3} = \text{the}$$

moments of the former,

$$\frac{f \times 143\cdot215}{3} \times s \times (Na_{,})^2 = \frac{sf \times 143\cdot215}{3} \times (143\cdot215)^2 = sf \times \frac{(143\cdot215)^3}{3}$$

= the moments of the latter.

$$\therefore \text{ their sum} = sf\left(\frac{(115\cdot66)^3 + (143\cdot215)^3}{3}\right) = sf\left(\frac{1547211 + 2937416}{3}\right)$$

$$= 1494875f. \ (s \text{ being} = 1) \qquad \text{(A.)}$$

2d. To obtain the moment of the forces of the vertical plates in the top and bottom cells of the tube.

For the moments of the forces in the top cells, estimating as above; first, the moment of the resistance of the vertical plates, on the supposition that these plates extend down to the neutral line, and then deducting from that result the estimated moments of resistance of the particles which had been assumed to extend from the top cells to the neutral line; we shall have, for the moments from the vertical plates between (A B) and ($a\,b$),

$$\frac{f\,(a-t)\,s'}{3}\,(a-t)^2 = \frac{f\,s'}{3}\,(a-t)^3 = \frac{f \times 6{\cdot}75}{3} \times (137{\cdot}41)^3,$$

the moment of the forces, supposing the vertical plates to extend from bottom of (A B) to the neutral line.

$$\frac{f\Big((\mathrm{N}\,a)+t\Big)\,s'}{3}\Big((\mathrm{N}a)+t\Big)^2 = \frac{f\,s'}{3}\Big((\mathrm{N}a)+t\Big)^3 = \frac{f\times 6{\cdot}75}{3} \times \Big(116{\cdot}41\Big)^3$$

the moments of the forces from the top of ($a\,b$) to the neutral line.

Taking the latter of these moments from the former, gives, for the moment from the vertical plates in the top, or compressed part of the tube,

$$\frac{f \times 6{\cdot}75}{3}\Big((137{\cdot}41)^3 - (116{\cdot}41)^3\Big) = 2288256\,f \qquad (1.)$$

In like manner the moments of the vertical plates in the bottom cells of the tube will be,

$$\frac{f\,(a_{,}-t_{,})\,s_{,}}{3}\,(a-t_{,})^2 = \frac{f\,s_{,}}{3}\,(a_{,}-t_{,})^3 = \frac{f\times 3{\cdot}5}{3}\,(165{\cdot}215)^3$$

$=$ those from the top of ($\mathrm{A}_{,}\,\mathrm{B}_{,}$) to the neutral line.

$$\frac{f\Big((\mathrm{N}\,a_{,})+t_{,}\Big)\,s_{,}}{3}\Big((\mathrm{N}\,a_{,})+t_{,}\Big)^2 = \frac{f\,s_{,}}{3}\Big((\mathrm{N}\,a_{,})+t_{,}\Big)^3 = \frac{f\times 3{\cdot}5}{3}\times(144{\cdot}215)^3$$

$=$ those from the bottom of ($a_{,}\,b_{,}$) to the neutral line.

Taking the latter moment from the former gives

$$\frac{f\times 3{\cdot}5}{3}\Big((165{\cdot}215)^3 - (144{\cdot}215)^3\Big) = \frac{f\times 3{\cdot}5}{3}(4509708 - 2999378)$$
$$= 1762052\,f \qquad (2.)$$

the moments of the forces of the plates in the bottom cells of the tube.

Adding together the moments in (1) and (2) gives,

$$2288256f + 1762052\,f = 4050308\,f \qquad (\mathrm{B.})$$

the moments from the vertical plates in the cells.

3rd. To obtain the moments of the forces of the horizontal plates (AB), (ab), $(A_{,}B_{,})$, and $(a_{,}b_{,})$, with those of the additional plates attached to them.

The moment from each of these is equal to the product of the three following values,—the strain upon a square inch of the plate,—the area of its section,—and the distance of its centre from the neutral line.

Hence, for the moment of the plates in (AB), the distance of the centre of gravity of which from the neutral line is $\left(a-\frac{t}{2}\right)$, we have

$$f\left(a-\frac{t}{2}\right) bt \times \left(a-\frac{t}{2}\right) = fbt\left(a-\frac{t}{2}\right)^2 = f \times 169 \times {\cdot}75 \times (137{\cdot}785)^2$$
$$= 2406311\,f \qquad (1.)$$

For those in (ab), the distance of its centre from the neutral line being $(Na)+\frac{t}{2}$, or $116{\cdot}035$, we have

$$f\left((Na)+\frac{t}{2}\right) bt \times \left((Na)+\frac{t}{2}\right) = fbt\left((Na)+\frac{t}{2}\right)^2 = fbt\,(116{\cdot}035)^2$$
$$= f \times 169 \times {\cdot}75\,(116{\cdot}035)^2 = 1706577\,f \qquad (2.)$$

To the top of (AB), the distance of which from (NO) is a, there are nine plates attached, the area of the section of which is $9 \times 9 \times \frac{1}{2} = 40{\cdot}5$ square inches.

The moment of their forces is therefore

$$fa \times 40{\cdot}5 \times a = f \times 40{\cdot}5\,(138{\cdot}16)^2 = 773071\,f \qquad (3.)$$

To the bottom of (ab), there are likewise attached seven plates, with an area of section $= 7 \times 9 \times {\cdot}5 = 31{\cdot}5$ square inches.

The moment from these is

$$f \times (Na) \times 31{\cdot}5 \times (Na) = f \times 31{\cdot}5\,(Na)^2 = f \times 31{\cdot}5\,(115{\cdot}66)^2$$
$$= 421383\,f \qquad (4.)$$

The moment of the forces of tension in $(A_{,}B_{,})$ is, in like manner,

$$f \times 165{\cdot}715 \times bt_{,} \times 165{\cdot}715 = fbt_{,}\,(165{\cdot}715)^2 = f \times 169 \times 1 \times (165{\cdot}715)^2$$
$$= 4640987\,f \qquad (5.)$$

And those in $(a_{,}b_{,})$

$$f \times 143{\cdot}715 \times bt_{,} \times 143{\cdot}715 = fbt_{,}\,(143{\cdot}715)^2 = f \times 169 \times 1 \times (143{\cdot}715)^2$$
$$= 3490526\,f \qquad (6.)$$

Adding together the values in (1), (2), (3), (4), (5), and (6), gives the moment of the forces from the horizontal plates,

$$2406311f + 1706577f + 773071f + 421383f + 4640987f + 3490526f$$
$$= 13438855f \qquad \text{(C.)}$$

The sum of the moments in (A), (B), and (C), or

$$1494875f + 4050308f + 13438855f = 18984038f$$
$$= \text{those of the forces from all the plates in the tube} \qquad \text{(D.)}$$

Moments of the Forces from the Angle-Irons.

Of these there are 40 in the corners of the top cells, and 32 in those of the bottom ones of the tube. The angle-irons in the top cells have each an area of 4 square inches in their section; and those in the lower cells of 2½ square inches. There are 18 angle-irons attached to the lower side of the plate (AB), at a distance $a - t = 137{\cdot}41$ inches from the neutral line. There are, likewise, 22 angle-irons attached to the plate (ab); 18 of these are attached to its upper side, at a distance $(\mathrm{N}a) + t = 116{\cdot}41$ inches from the neutral line; and the other 4, at the bottom of (ab), 115·66 inches from the neutral line. There are 14 angle-irons attached to the top of the bottom plate $(\mathrm{A}_{,}\mathrm{B}_{,})$, at a distance of 165·215 inches from the neutral line; 14 attached to the bottom of $(a_{,}b_{,})$, at a distance of 144·215 inches; and 4 to its top, 143·215 inches from the neutral line.

Moments of angle-irons attached to (AB),

$$f(a-t) \times 18 \times 4\,(a-t) = f \times 72\,(a-t)^2 = f \times 72\,(137{\cdot}41)^2$$
$$= 1359468f \qquad (1.)$$

Moments of those attached to top of (ab),

$$f\big((\mathrm{N}a)+t\big) \times 18 \times 4\,\big((\mathrm{N}a)+t\big) = f \times 72\,\big((\mathrm{N}a)+t\big)^2 = f \times 72\,(116{\cdot}41)^2$$
$$= 975692f \qquad (2.)$$

Moments of those attached to bottom of (ab),

$$f \times 115{\cdot}66 \times 4 \times 4 \times 115{\cdot}66 = f \times 16\,(115{\cdot}66)^2 = 214035f \quad (3.)$$

Moments of angle-irons at the top of $(\mathrm{A}_{,}\mathrm{B}_{,})$,

$$f \times 165{\cdot}215 \times 14 \times 2{\cdot}5 \times 165{\cdot}215 = f \times 35\,(165{\cdot}215)^2 = 955359f \quad (4.)$$

Moments of those at the bottom of $(a_{\prime}b_{\prime})$,

$$f \times 144{\cdot}215 \times 14 \times 2{\cdot}5 \times 144{\cdot}215 = f \times 35\,(144{\cdot}215)^2 = 727928f \quad (5.)$$

Moments of those at the top of $(a_{\prime}b_{\prime})$,

$$f \times 143{\cdot}215 \times 4 \times 2{\cdot}5 \times 143{\cdot}215 = f \times 10\,(143{\cdot}215)^2 = 205105f \quad (6.)$$

Adding together the results in (1), (2), and (3), we have

$$1359468f + 975692f + 214035f = 2549195f \qquad (E.)$$

the moments of the forces from the compressed angle-irons.

The sum of the results in (4), (5), and (6), gives

$$955359f + 727928f + 205105f = 1888392f, \qquad (F.)$$

the moments of the forces of the extended angle-irons, supposing them to act with their full tensile force.

The whole resisting forces in the tube arise from the plates and the angle-irons. Taking the several moments from these, as in (D), (E), and (F), we have

Moment from plates..............	18,984,038f	
,, compressed angle-irons	2,549,195f	
,, extended ,, ...	1,888,392f	
Sum of the moments	23,421,625f	(G.)

It is probable that the extended angle-irons may, from imperfect joining at the ends, not act with their whole tensile strength; hence, taking the moment from them at one-half of what it is computed, or 944196 f, gives for the whole moment

$$22{,}477{,}429f \qquad (H.)$$

It is here supposed, that the position of the neutral line is not sensibly changed by these different suppositions with respect to the action of the angle-irons.

To Compute the Strength from the preceding Moments.

If we consider, as before, the tube to be supported at the ends, and loaded in the middle, each end will have to sustain half the weight, and its distance from the middle will be half the span.

Hence, if w be the weight in the middle of the tube, l the span, or distance between the supports, and G, or H, the moments in (G) or (H), we have

$$\frac{w}{2} \times \frac{l}{2} = \text{G or H.}$$

Putting $mf =$ the moments of the forces in (G), or (H), we have

$$w = \frac{4mf}{l}.$$

The strength depends upon f, which is a quantity such that $a \times f =$ the force per square inch, with which the tube is compressed at the top; or $a_{,} \times f$, the force with which it is extended at the bottom.

If we suppose it, as before, to be compressed at the top, to the extent of eight tons per square inch, then $a \times f = 8$; and since a, the distance of the top from the neutral line, is 138·16 inches,

$$\therefore \quad f = \frac{8}{138{\cdot}16} = {\cdot}0579 \text{ ton.}$$

Substituting this for f, in the formula above, gives

$$w = \frac{4mf}{l} = \frac{4m \times {\cdot}0579}{l} = \frac{{\cdot}2316 \times m}{l} \text{ tons,}$$

the weight which a tube, of the lateral dimensions of that at Conway would support, when it was compressed at the top, to the extent of eight tons per square inch, which, I conceive, is the greatest strain to which it should be subjected.

The distance between the supports, on which the Conway Tube will be laid, is 400 feet = 4800 inches, and taking the values of m, from those in (G) and (H), we have

$$w = \frac{{\cdot}2316 \times 23421626}{4800} = 1130{\cdot}09 \text{ tons,}$$

when the angle-irons are considered to act with the full force due to the material.

Or, $$w = \frac{{\cdot}2316 \times 22477429}{4800} = 1084{\cdot}5 \text{ tons,}$$

when the bottom angle-irons are only considered as acting with half their tensile force.

Taking the lower estimate of the strength, it appears that 1084·5 tons, laid on the middle of the tube, the pressure from its own weight being included, would cause the plates of the upper cells to be compressed, in the direction of their lengths, to the extent of eight tons per square inch; and, since the distances of the top and bottom of the tube, from the neutral line, are 138·16 inches and 166·215 inches respectively, the simultaneous strain in the plates, at the bottom of the tube, would be

$$\frac{166{\cdot}215}{138{\cdot}16} \times 8 = 9{\cdot}6 \text{ tons.}$$

Supposing the elasticity to remain uninjured, and the top plates of the tube to be compressed, in the direction of their lengths, to the extent of 12 tons per square inch, or half as much again as in former case, the extension per square inch, at the bottom, would be $\frac{3}{2} \times 9{\cdot}6 = 14{\cdot}4$ tons, and the weight which the tube would be supporting, including that from its own mass, would be $\frac{3 \times 1084{\cdot}5}{2} = 1626{\cdot}7$ tons.

It has been shewn from the results of several experiments, that wrought-iron, strained by *tension*, beyond about 15 tons per square inch, or by *compression* beyond 12 tons, would be destroyed for all practical purposes. It was likewise shewn, that a weight of 12 tons per square inch produced a decrement of about $\frac{1}{863}$rd of the length.

It would appear from the preceding computation and remarks, that a tube of these dimensions, if made without joints, and loaded without vibration, would bear a weight in the middle, including the pressure from its own weight, of 1627 tons, without entirely destroying the utility of the material. But plates united by riveting in the best manner, in common use, are weaker than plates without joints, in the ratio of 3 to 2 nearly; we ought, therefore, to reduce the computed breaking-weight in that ratio, or even a greater; since the computation is made on the supposition of the tube being without joints, and loaded without vibration.

Calculation of the Deflection of the proposed Tubes.

The probable deflection of the first of the two forms of tubes, of which the strength was calculated, was determined by Mr. Hodgkinson in December 1846, as follows :—

The longitudinal compression of wrought-iron, from experiments before detailed, was $\frac{1}{863}$rd of the length, from a direct pressure of 12 tons per square inch, with which pressure the practical utility of the material may be considered as destroyed.

The modulus of elasticity would thus be 23,243,179 lbs. which weight would extend a one-inch bar to double its length. From experiments on the longitudinal extension, it has been determined at 23,865,624, and from others 24,446,394, the mean of the three being 23,851,732 lbs. According to Tredgold, the modulus is 24,920,000 lbs. In the following computations it is taken at 24,000,000 lbs., or 10,714 tons per square inch, which quantity is called E. In some of the experiments on the compression of tubes, they appeared to be compressed $\frac{1}{600}$th of the length by 12 tons per square inch.

First, to determine the radius of curvature at the centre of the given tube.

Since a bar of wrought-iron will be compressed $\frac{1}{863}$rd of its length, without destroying its utility, wherever the neutral line of the bent tube may be, its concave side at the part of greatest strain may be reduced in the ratio of 863 to 862.

Let ϱ be the radius of curvature of the neutral line, and a the distance of the concave side from that line, then $\varrho - a$ will be the radius of curvature of the concave side, the distance of which from the neutral line is a.

We shall then have,

$$\varrho : \varrho - a :: 863 : 862 ;$$

Whence, $862\,\varrho = 863\,\varrho - 863\,a, \;\therefore\; \varrho = 863\,a.$

In the proposed tube $a = 138{\cdot}73$ inches,

$$\therefore \varrho = 863 \times 138{\cdot}73 = 119723{\cdot}99 \text{ inches} = 9977 \text{ feet.}$$

Whence the radius of curvature of the tube, when bent to the utmost it will bear, without destroying the utility of the metal by compression, is 9977 feet = 1·9 mile, nearly; and the force exerted by the particles, contracted by $\frac{1}{863}$rd of their length, is 26,933 lbs. or 12 tons per square inch nearly.

To find the Connexion between the Radius of Curvature, and the value of f, previously employed.

The figure annexed, being supposed to represent the tube when bent.

Put ϱ = (A O) the radius of curvature of the neutral line;
a = (B C) the distance of the neutral line from the concave side;
e = (A B) any small portion of the length of the neutral line;
e' = (C D) the decrement of the concave side, answering to the part (A B);
E = the force necessary to elongate or shorten a bar of wrought-iron, 1 inch square, by a quantity equal to the length e of the bar, = 24,000,000 lbs. = 10714·3 tons;
fa = the force per square inch, necessary to produce the compression e'.

The line (B C) being drawn parallel to (A O), we have, from similar triangles,

(A O) : (B C) :: (A B) : (C D), or

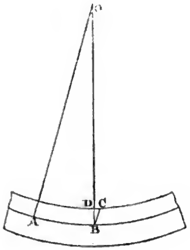
$$\varrho : a :: e : e'$$

But $e : e' :: \mathrm{E} : fa$

Whence $\mathrm{E} : fa :: \varrho : a$

$$\therefore \frac{\mathrm{E}}{\varrho} = \frac{fa}{a} = f,$$

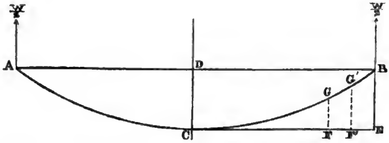
We have, therefore, $\frac{\mathrm{E}}{\varrho} = f$, whatever the flexure of the tube may be.



To find the Deflection of the Tube.

When a uniform beam, or other flexible body, is placed on supports at its ends, and loaded with a weight, w, in the middle, if A C B represent the beam, the deflection C D will be the same as if the beam were fixed firmly in the middle, and drawn up by a weight $\frac{w}{2}$ at each end.

Let $l = (\mathrm{C\,E}) =$ half the length of the beam, nearly;
$x, y =$ the horizontal and vertical co-ordinates of any point, G, in the curve, referred to C as the origin;
$\varrho =$ the radius of curvature at the point G;
$\delta =$ the distance E B, or the whole deflection C D.



Then, from above, $\frac{\mathrm{E}}{\varrho} = f$, whatever the value of f may be. But it has been shewn that the moment of the forces in the first design for the Conway Tube was $m f$, where m varied, according to different suppositions, between 22,744,508 and 20,495,814, and the mean 21,620,161 as in (C), was adopted.

But $m f = \frac{w}{2}(l - x)$; and since $f = \frac{\mathrm{E}}{\varrho}$, $m\,\frac{\mathrm{E}}{\varrho} = \frac{w}{2}(l - x)$.

But $\frac{1}{\varrho} = \frac{\frac{d^2 y}{d x^2}}{\left(1 + \frac{d y^2}{d x^2}\right)^{\frac{3}{2}}}$, and when the deflection is small, $\frac{d y^2}{d x^2}$ may be neglected, we shall then have,

$$\frac{1}{\varrho} = \frac{d^2 y}{d x^2}; \text{ and since } \frac{m\,\mathrm{E}}{\varrho} = \frac{w}{2}(l - x),$$

$$\therefore\ m\,\mathrm{E}\,\frac{d^2 y}{d x^2} = \frac{w}{2}(l - x).$$

Integrating $$m\,\mathrm{E}\,\frac{d y}{d x} = \frac{w}{2}\left(l\,x - \frac{x^2}{2}\right)$$

$$m\,\mathrm{E}\,y = \frac{w}{2}\left(\frac{l\,x^2}{2} - \frac{x^3}{6}\right). \quad \text{When } x = l,\ y = \delta;$$

$$\therefore\ m\,\mathrm{E}\,\delta = \frac{w}{2} \times \frac{l^3}{3}, \qquad \delta = \frac{w\,l^3}{6\,m\,\mathrm{E}},$$

where $m = 21{,}620{,}161$, and $\mathrm{E} = 24{,}000{,}000$ lbs. $= 10714{\cdot}3$ tons.

If the weight w be taken in tons; then,

$$\delta = \frac{w\,l^3}{6 \times 21620161 \times 10714{\cdot}3} = \frac{w\,l^3}{1{,}389{,}869{,}346{,}014}$$

In the Conway Tube, $l = 200$ feet $= 2400$ inches:

$$\therefore\ \delta = \frac{w\,(2400)^3}{1{,}389{,}869{,}346{,}014} = \frac{w}{100{\cdot}540}$$

1st. If $w = 1039{\cdot}$ tons, which would in that tube produce a pressure on the concave side, equal to 8 tons per square inch; the angle-irons at the bottom being supposed to act with half their tensile force, $\delta = \frac{w}{100{\cdot}54} = \frac{1039}{100{\cdot}54} = 10{\cdot}33$ inches = the ordinate B E, at the end of the tube, or the deflection C D, in the middle.

This deflection is that which would accrue from the tube if it were made without joints, and was of small weight comparatively with the load in the middle. But the weight of the tube is great, and the riveted joints may be expected to adjust themselves with the strain, and increase the deflection beyond the computed amount.

2d. If $w = 1558{\cdot}2$ tons, the pressure which would strain the tube to 12 tons per square inch at the top, and 15·57 tons at the bottom,

Then $$\delta = \frac{w}{100{\cdot}54} = \frac{1558{\cdot}2}{100{\cdot}54} = 15{\cdot}5 \text{ inches nearly.}$$

To determine the deflection of a beam, caused by its own weight. It has been shewn by various writers, and might easily be demonstrated here, that when the ends are rested on supports, the deflection of a uniform beam, from a weight uniformly distributed over its length, is to the deflection from the same weight applied in the middle, as 5 to 8.—Tredgold, *Essay on Cast-Iron, Art.* 62.

Deflection of the first proposed Tube from its own weight.

Suppose the tube to be uniform, and its weight, together with that of the platform within it, to be 900 tons, then the deflection of the tube, in consequence, of its weight spread uniformly over it, would, from the last article, be,

$$\delta = \frac{5}{8} \times \frac{w}{100{\cdot}54} = \frac{5 \times 900}{8 \times 100{\cdot}54} = 5{\cdot}59 \text{ inches,}$$

or a little more, in consequence of riveting. It would therefore appear that the deflection from the weight of the tube is to the utmost deflection which the tube could sustain without serious injury as 5·59 to 15·5, or as 10 to 28 nearly.

To find the deflection of the tube from other principles, supposing the curve to be a portion of a parabola, or of a circle, and the curvature in the middle to be the greatest that the tube could sustain without destroying the utility of the material.

The radius of curvature was found to be 9977 feet.

1st. Suppose the curve to be a parabola, of which the equation is $y^2 = 4\,m\,x$,

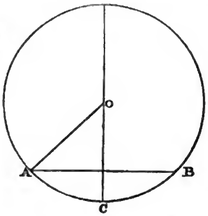
Then the deflection $x = \dfrac{y^2}{4\,m}$.

In this curve, $2\,m$, the semi-parameter, is equal to the radius of curvature at the vertex.

But from above, $2\,m = 9977$ feet, and, in the Conway Tube, $y = 200$ feet.

$$\therefore\ x = \frac{y^2}{4\,m} = \frac{(200)^2}{2 \times 9977} = 2{\cdot}00 \text{ feet} = 24 \text{ inches}$$

nearly.



2d. If the curve be a circular arc.

Then $\sqrt{(\text{A O})^2 - (\text{A B})^2} = (\text{O B})$;

$(\text{B C}) = (\text{C O}) - (\text{O B}) = (\text{A O}) - (\text{O B})$.

But $(\text{A O}) = 9977$ feet; $(\text{A B}) = 200$ feet.

$\therefore\ (\text{B C}) = 2{\cdot}01$ feet $= 24{\cdot}12$ inches.

Both of these curves, especially the circle, which is everywhere equally bent, must obviously give a larger deflection, for the same length and curvature at C, than the proper curve of the tube, which is very little bent towards the ends. The relative deflections of the tube, estimated as an elastic curve, and a circle, or parabola, are 15·5 inches, and 24 inches nearly.

The deflection of the second form of tube was not computed by Mr. Hodgkinson, at the time of the foregoing investigation of its strength, but it has since been investigated as follows:—The radius of curvature, with a compression of 12 tons per square inch, has been shewn to be equal to 863 a, where a is the distance of the top from the neutral line. In the second form $a = 138{\cdot}16$, hence its radius of curvature under the same assumptions, will be $863 \times 138{\cdot}16 = 9936$ feet $= 1{\cdot}88$ mile.

Supposing the tubes to be uniform throughout, we should have,

$\delta = \frac{w\,l^3}{6\,m\,\text{E}}$, the values of which, applied in the present tube, give

$$\delta = \frac{(2400)^3 \times w}{6 \times 22477429 \times 10714{\cdot}3} = {\cdot}00956691\ w\ ;$$

where δ is the deflection, and w the weight in the middle of the tube.

If $w = 1626{\cdot}7$ tons, the weight which would compress the tube to 12 tons per square inch at the top,

$$\delta = {\cdot}00956691 \times 1626{\cdot}7 = 15{\cdot}56 \text{ inches,}$$

the utmost deflection it might be expected to bear with safety.

The tube, if bent by its own weight, would be deflected $\frac{5}{8}$ths of what it would have been, if the same weight had been suspended from the middle, assuming the weight at 1300 tons nearly; the deflection from the weight alone might, therefore, be expected to be,

$$\delta = {\cdot}00956691 \times \tfrac{5}{8} \times 1300 = 7{\cdot}773 \text{ inches.}$$

CHAPTER II.

STRENGTH AND DEFLECTION OF THE CONWAY BRIDGE AS COMPLETED.

PREVIOUS to the application of more exact and general reasoning, we shall first determine the strength and deflection of this beam from the elementary formulæ given in previous chapters; and to avoid constant reference, such practical rules as have been employed are here repeated.

1. The strength of similar beams is as the square, and the weight as the cube of their lineal dimensions.
2. If a represent the sectional area at the centre, d the depth, and l the length of any beam in inches, and C be a constant derived from a similar beam, then for the breaking-weight at the centre we have—

$$W = \frac{a\,d}{l} C.$$

The value of C has been determined experimentally for the following forms :—

Wrought-iron.	Value of C in Tons.	Page.
Rectangular tubes, with thick top and bottom plates, and thin sides, as in the large model, or the tubular bridges	26·7	193
Rectangular tubes of uniform thickness	23·5	436
Elliptical tubes of uniform thickness	22·3	436
Circular tubes of uniform thickness	20·9	436
New rectangular bars	15·3	451
Rectangular bars previously strained	22·3	451
New round bars	9·0	106

Cast-iron.	Value of C in Tons.	Page.
Uniform rectangular tubes	10·96	434
Uniform elliptical tubes	12·01	434
Uniform circular tubes	11·42	434
Uniform square tubes	13·67	434
Small rectangular bars	13·6	445
Large rectangular bars	9·0	445
Round bars, small	8·0	106
Miscellaneous.		
Rectangular beams of deal	1·45	453

3. If a represent the sectional area of the bottom flange of a girder or tube, we have—

For wrought-iron $W = \frac{a\,d}{l}\,74{\cdot}4$ tons. (Page 193.)

For cast-iron $W = \frac{a\,d}{l}\,26$ tons. (Page 273.)

4. In a flanged beam loaded uniformly, if W = the weight distributed, and l the length in terms of the depth (*i. e.*, calling the depth unity), and omitting the strength of the vertical rib, we have for the strain tending to crush or tear asunder the flanges—

$$S = \frac{W\,l}{8}. \quad \text{(Page 195.)}$$

Hence the strain per square inch may be found.

For the Deflection of Beams.

5. The deflection of a rectangular beam increases as the load and as the cube of the length, and inversely as the sectional area, multiplied by the square of the depth.

6. The deflection of a beam from a weight laid on the

middle is greater than the deflection of the same beam when the weight is equally distributed in the proportion of 5 : 8.

7. The deflection of similar beams from their own weight is as the square of their lineal dimensions.
8. The deflection of similar beams from weight placed at the centre is directly as the weight, and inversely as the lineal dimensions.
9. The ultimate deflection of similar tubes is directly as their length.

The Strength of the Conway Bridge.

The Conway Tube is analogous, though not strictly similar, to the large model beam described in Section II. chapter 3. The most important variation is in the construction of the bottom and sides.

If we multiply the depth, length, and breadth of the model by $5\frac{1}{3}$, we shall have a tube,

$5\frac{1}{3}$ × 75 ft. = 400 feet long.
$5\frac{1}{3}$ × 4′ 6″ = 24 feet deep.
$5\frac{1}{3}$ × 2′ 8″ = 14 feet broad.

And its breaking-weight at the middle, or its absolute strength, would be $5\frac{1}{3} \times 89 = 475$ tons.

The sectional area of the bottom of the model was 22·4 square inches, and the sectional area of the bottom of this new model would therefore be $22{\cdot}4 \times 5\frac{1}{3} = 119{\cdot}5$ sq. inches.

The sectional area of the bottom, at the centre of the Conway Bridge, is 526 square inches.

Now, as regards failure at the bottom, the strength of a tube is proportional to the sectional area of the plates; consequently, if the plates of this new model were so increased in thickness as to give a sectional area of 535 square inches to the bottom, we should have its absolute strength as follows:—

As 119·5 sq. in. : 535 sq. in. : : 475 tons : 2126 tons.

Such a tube would closely resemble the Conway Tube, except as regards the depth.

The depth of the enlarged model, from the bottom to the centre of the top cells, would be 22·5 feet.

The depth of the Conway Bridge, from the centre of the bottom cells to the centre of the top cells, is 23·7 feet; therefore,

(A.) As 22·5 ft. : 23·7 ft. : : 2126 tons : 2239 tons.

Therefore the central load the Conway Bridge would bear, in addition to its own weight, is

$$2239 - \frac{1112}{2} = 1683 \text{ tons.}$$

Again, we have seen that when the model failed the tension per square inch at the bottom averaged 18·6 tons, which would therefore be the strain produced by a weight of 2239 tons at the centre of the Conway Bridge. Hence, for the strain per inch from its own weight, we have,

$$\text{As } 2239 : \frac{1112}{2} :: 18\cdot6 : 4\cdot62 \text{ tons,}$$

which is the strain per square inch, at the centre of the bridge, from its own weight.

If the Conway Bridge were in every respect similar to the model, its weight should be $(5\frac{1}{3})^3 \times 6\cdot25 = 946\cdot4$ tons, instead of 1112. The sectional area of the bottom should be $(5\frac{1}{3})^2 \times 22\cdot4 = 640$ sq. inches, instead of 535. The whole sectional area should similarly be 1664 sq. inches, instead of 1438. Moreover, its strength by (1) should be $(5\frac{1}{3})^2 \times 89\cdot24 = 2534$, instead of 2239.

Thus, if the Conway Bridge were similar to the model, it would weigh 166 tons less than it actually does, while its absolute strength would be 295 tons greater, or it would be 13 per cent stronger and nearly 15 per cent lighter than it is.

The additional weight is principally requisite for stiffening and strengthening the sides. The pillars of angle and T-iron weighing 150 tons, the principal falling off in strength arises from the decrease in the sectional area of the bottom.

We thus see how great an error we should commit by calculating the strength of this bridge as a similar beam to the model, and, secondly, how soon we should come to a practical limit in the magnitude of such beams, from the great weight necessary for stiffening the sides.

From the formula (2), we should have the absolute strength of the Conway Tube,

$$W = \frac{1438 \times 23{\cdot}7}{400}\, 26{\cdot}7 = 2275 \text{ tons.} \tag*{(B.)}$$

Again, from the formula (3), we have, as regards failure at the bottom,

$$W = \frac{535 \times 23{\cdot}7}{400}\, 74{\cdot}4 = 2358 \text{ tons.} \tag*{(C.)}$$

As regards failure at the top (see page 194), we have,

$$W = \frac{645 \times 23{\cdot}7}{400}\, 59 = 2253 \text{ tons.} \tag*{(D.)}$$

From page 188, we should have the area of the bottom to that of the top as

14·8 : 18·6

or as 100 : 125 nearly.

The actual ratio is 535 : 645

or 100 : 120

Lastly, we may calculate the strength independently, for the bridge weighs 1112 tons between the supports, and may be considered as a beam without weight loaded with 556 tons at the centre.

The strain at the centre tending to tear asunder the bottom or crush the top, will be,

$$\frac{278 \times 200}{23 \cdot 7} \text{ tons} = 2346 \text{ tons},$$

and

$$\frac{2346}{535} = 4 \cdot 38 \text{ tons per square inch tensile strain.}$$

Now the ultimate tensile strain of riveted plates (see page 188) is 18·6; therefore,

(E.) As 4·38 : 18·6 : : 556 : 2360 tons.

The results obtained are so similar, that we shall take the mean as the absolute ultimate strength of the Conway Bridge.

From A we have	2239	tons.
B	2275	
C	2358	
D	2253	
E	2346	
Mean of the whole	2300	

Therefore the central load the bridge would bear, or its available strength, will be

$$2300 - \frac{1112}{2} \text{ tons} = 1744 \text{ tons},$$

or 3488 tons distributed over its whole length, or 8·72 tons per foot run; while a train, consisting wholly of locomotives, only weighs one ton per foot run. It will, therefore, carry, in addition to its own weight, above eight times as much as can ever be placed upon it.

The strain per square inch, moreover, does not exceed 4½ tons per square inch, and is less than the strain on the chains of the Menai Suspension-bridge, and many other permanent structures; and from (4), the strain caused by a train weighing one ton per foot, would be

$$\frac{400 \times 18{\cdot}3}{8} = 915 \text{ tons,}$$

or $$\frac{915}{535} = 1{\cdot}7 \text{ tons per square inch at the bottom, in addition to the strain from its own weight.}$$

The total strain for the tube full of locomotives being only 6·2 tons per square inch.

It is evident that in such calculations we have assumed the top to resist buckling similarly to the top of the model. Its strength in this respect was ascertained on principles before explained; but the crushing of the single cell, similar to those employed in the top of the tube, as described at page 364, was a satisfactory confirmation of the views entertained.

Deflection of the Conway Bridge.

It will be interesting to compare the original calculations of the deflection of the Conway Bridge with the observed result.

The first estimate of the probable deflection of the tubes was, as we have seen, made by Mr. Stephenson, who assigned 12 inches as the probable deflection of the Britannia Tube.

Good data for determining the deflection were afforded by the experiments on the large model, Section II.

In the first three experiments the observations are not trustworthy; but in the three last experiments the deflections were found to vary very nearly as the weight, even up to the time of failure, and the deflection was very nearly ·06 inch for every ton of central load. Now the weight of the model was 5·13 tons, equally distributed, and 1·14 ton employed in strengthening the centre; therefore the deflection of the tube, from its own weight, from formula (6) would be:—

		Inch.
	$\frac{5}{8}$ of $5·13 \times ·06 =$	·1924
and about		
	$\frac{7}{8}$ of $1·14 \times ·06 =$	·0598
	Total	·2522

And by (7) the deflection of the Conway Tube, if it were perfectly similar to the model, would, from its own weight, be $(5\frac{1}{3})^2 \times ·2522 = 7·17$ inches.

But we have seen that the tube, if similar to the model, would have been 15 per cent lighter than it is, though the sectional area would have been considerably greater. The deflection of the Conway Tube was therefore estimated at 8 inches, which was the amount of camber intended to be given to the tubes in order that the bottom might be ultimately as near as possible a straight line.

The failure of the platform during construction, and the difficulty of working true on such foundations with heavy masses of plates, left the camber of the first tube 6·49 inches at the centre, and 7·31 at a distance of 50 feet from the centre, as at page 638. The camber of the second was 8·44 inches at the centre.

The difficulty of determining the deflection accurately when the tube was complete, was very considerable. The effect of change of temperature vitiated all the first observations, and the wedging up of the platforms interfered with the determination of the normal figure of the bottom.

The deflection of the first tube was measured internally on the angle-iron which unites the sides with the bottom. No reference could consequently be made to these original data, when the tube was permanently fixed; but in the second tube the deflection was measured internally on the transverse plates which carry the permanent way, and permanent notches are cut in these plates for the foot of the staff, for future reference.

The deflection of the first tube, from its own weight, immediately on removal of the platform, was 7·94, and of the second, 8·15, the mean being 8·04.

The deflection of both tubes increased after the lapse of some time. The first tube, after being tested, attained in four days, a deflection of 8·81; and the second, without testing, attained, in two days, a deflection of 9·16, the mean being 8·98 inches. The addition of the permanent way, and the increase of length consequent on permanently fixing the tube, ultimately left the deflection of the second tube 10·33, in January 1849, and after being twelve months in use, the deflection in January 1850, was found to be 10·30.

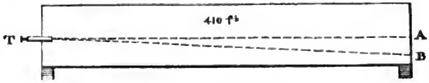
In ascertaining the deflections of the second tube, observations were made at night, when the temperature of the tube is uniform.

The immediate effect of the deflection of the tube is evidently to incline towards each other the vertical castings at each extremity. This inclination is produced by the compression of the top and the extension of the bottom. It will be seen hereafter that the determination of the exact inclination thus induced was an important practical inquiry. For this purpose plumb-lines were suspended at each extremity, previous to the removal of the platform, and the inclination as the tube descended was thus observed.

The distance between the centre of suspension of the plumb-lines and the arcs measured was 14 feet.

A deflection of 8·15 inches produced a motion of ·78 inch on this arc at the Conway extremity, and ·85 inch at the Chester extremity, or a mean motion of ·815 inch at each end.

This inclination was equally well measured, and with a much longer radius, by the telescope attached to the cast-iron frame at right angles to the plumb-line. It was thus requisite, in determining the deflection, to re-adjust the telescope at every observation to cut the fixed mark on the frame at the opposite extremity. Thus the telescope T attached to the side of the tube was made to cut the fixed mark A.



On placing 236 tons on the tube equally distributed over 300 feet, a certain deflection was produced, and the direction of the line of sight was no longer T A, but on account of the inclination of the frame at T, the line of sight had passed through the angle A T B, the chord A B measuring 4 inches, with the above weight. It was thus requisite to re-adjust the telescope to bisect the mark A previous to reading the deflection, which was thus found to be 1·4 inch as recorded.

The deflection of the second tube from an ordinary train passing through at the usual speed was carefully ascertained January 28, 1850. The train consisted of engine and tender, 25 tons; one first-class, 5 tons; one second-class, 4½ tons; two third-class, 4½ tons each; ten trucks, 2½ tons each; with a load of 18 tons: total weight, 100 tons. The deflection, measured from a fixed mark on the other tube, was ·47 inch.

The weight of the Conway Tube between the supports is 1150 tons distributed nearly equally throughout; and the deflection from this weight being 8·04 inches, the deflection per ton from weight equally distributed is ·0069 inch; consequently, from Ch. iii. 11, the deflection per ton from weight placed at the centre should be $\frac{8}{5} \cdot 0069 = \cdot 01104$ inch; and this will be found to agree very accurately with the observed deflections on testing the tubes.

Again, we have found the breaking-weight of this bridge to be 1744 tons, the ultimate deflection which this weight would produce, in addition to the present deflection, is therefore $1744 \times \cdot 01104 = 19 \cdot 25$ inches, or the whole deflection $= 19 \cdot 25 + 8 \cdot 04 = 27 \cdot 29$. But if, instead of 1744 tons placed at the centre, the tube were broken by 3488 tons equally distributed, the deflection in this case would be $3488 \times \cdot 0069 = 24 \cdot 76$ inches, or the whole deflection $24 \cdot 76 + 8 \cdot 04 = 32 \cdot 8$ inches; that is, though the central strain is the same in both cases when the tube fails, yet the ultimate deflection from the tube loaded all over will be 5·5 inches more than that from half the same weight placed at the centre. Hence the amount of the deflection of a beam is not necessarily a test of the strain to which it is subjected.

The deflection may be determined on other considerations, thus, by (8), since the deflection of the model was ·06 inch per ton at the centre, the deflection at the Conway should be $\frac{\cdot 06}{5\frac{1}{3}} = \cdot 0112$ per ton, instead of ·01104, as found above.

Again, the ultimate deflection of the large model was 4·88 inches + ·252 from its own weight $= 5 \cdot 132$ inches; and therefore, by (9) the ultimate deflection of the Conway should be $5\frac{1}{3} \times 5 \cdot 132 = 27 \cdot 37$ inches from weight at the centre, which agrees very closely with the results obtained as above.

APPLICATION TO THE CONWAY BRIDGE OF THE GENERAL FORMULÆ DEDUCED IN CHAPS. II. AND III., SECTION III.

Strength of the Bridge.

In accordance with the remark on page 240, we have here to determine the ratio between the weight which the tube is supporting, and the maximum longitudinal strain, either of extension or compression, on the fibres of which it is composed.

We shall consider the beam as loaded uniformly over its length, and the strength will therefore be found from Equation XXIII., page 256,

$$\frac{\mu l}{f} = \frac{8}{c\,l}\,\mathrm{I}.$$

Where l = length of beam, μl = the load distributed over it, I = the moment of inertia of the section at the middle of the beam, and f = the longitudinal strain per square inch on a fibre in that section, whose distance from the neutral line = c.

The value of I is thus found for the Conway Bridge, all the dimensions being taken in feet for the convenience of calculation.

Referring to Equation X., on page 248, we have, for the moment of inertia of a rectangular tube,

$$\mathrm{I} = \left(a_1 + \frac{a_3}{3}\right) h_1{}^2 + \left(a^2 + \frac{a_4}{3}\right) h_2{}^2,$$

where a_1 and a_2 represent the areas of the bottom and top respectively, h_1 and h_2 their mean distances from the neutral axis, and a_3 and a_4 the areas of the portions of the sides below and above the neutral line.

At the centre section of the Conway Tube:

a_1 .... = 3·73 square feet.
a_2 .... = 4·48 ,,

The mean depth from centre to centre of cells at this part of the beam is 23·6 feet, and the neutral axis is found by the usual rules to be 12·6 feet from the bottom. Hence,

h_1 .... = 12·6 feet.
h_2 .... = 11·0 ,,

The total area of the sides is 1·79 square feet, wherefore,

a_3 .... = 0·96 square feet.
a_4 .... = 0·83 ,,

According to these dimensions, we have,

$$I = \left(3{\cdot}73 + \frac{0{\cdot}96}{3}\right) 12{\cdot}6^2 + \left(4{\cdot}48 + \frac{0{\cdot}83}{3}\right) 11^2 = 1221.$$

Substituting, therefore, this value and the value of l (= 400 feet) in the above equation,

$$\frac{\mu\, l}{f} = \frac{8 \times 1221}{400\, c} = \frac{24{\cdot}42}{c},$$

from which may be found either the strain corresponding to a given weight, or the weight which will produce a given strain.

Let us first inquire what strain is produced by the weight of the tube itself, $\mu\, l$ being then 1112 tons; so that

$$\frac{1112}{f} = \frac{24{\cdot}42}{c},$$

or

$$f = 45{\cdot}5\ c.$$

Now, the total depth of the beam at the centre being 25·4 feet, we have,

For the bottom plates .... $c = 13{\cdot}6$ feet.
For the top plates .... $c = 11{\cdot}8$ „

Therefore, for the strain on the bottom,

$$f = 45{\cdot}5 \times 13{\cdot}6 = 619 \text{ tons per square foot,}$$
$$= 4{\cdot}3 \text{ tons per square inch.}$$

For the strain on the top plates,

$$f = 45{\cdot}5 \times 11{\cdot}8 = 537 \text{ tons per square foot,}$$
$$= 3{\cdot}7 \text{ tons per square inch.}$$

We will now perform the converse of the above process, by computing what weight will produce a given strain, taking, for an example, the ultimate strain which the material will bear. This strain has already been shewn to be,

For the bottom plates, $f = 18{\cdot}6$ tons per square inch,
($= 2678$ tons per square foot).
For the top plates, $f = 14{\cdot}8$ tons per square inch,
($= 2131$ tons per square foot).

Returning, therefore, to the equation above deduced, we have, for the bottom plates,

$$\frac{\mu\, l}{2678} = \frac{24{\cdot}42}{13{\cdot}6},$$

or

$$\mu\, l = 4826 \text{ tons},$$

the weight which, equally distributed along the beam (including its own weight), would break it by tearing asunder the plates at the bottom. For the top plates,

$$\frac{\mu\, l}{2131} = \frac{24{\cdot}42}{11{\cdot}8},$$

or

$$\mu\, l = 4410 \text{ tons},$$

the weight which would break the tube by crushing the top. The mean of these is 4618 tons. It will be seen how closely the above computations of the strength of the tube correspond with those previously obtained by an entirely different process.

Deflection of the Bridge.

The deflection of a beam loaded uniformly over its length is given by Equation XXXIX., that is—

$$\mathrm{E\,I}\,y = \frac{\mu}{24}(x^4 - 2\,l\,x^3 + l^3\,x).$$

Where E = modulus of elasticity; I = moment of inertia of the section; l = length; μ = weight per lineal unit; and y = the deflection at any point distant x from the end of the beam.

It must be remarked that in the deduction of this and other formulæ for deflection, the moment of inertia has been assumed the same at every part of the length of the beam; this is not true for the Conway Bridge, the value of I diminishing gradually from the middle towards the ends. The introduction of a variable moment of inertia into the expressions for deflection is very complicated, unless it can be expressed in simple terms of the length, which is seldom the case. We may, therefore, take a mean value, and consider this value as constant throughout the length, which will give the deflection without much error.

This mean value may be found by taking the moment of inertia at several points, thus, each value being found by the same process as on page 755.

Values of I, *the Moment of Inertia.*

At end of tube	=	688
Half-way between end and centre	=	943
At the centre	=	1221
Half-way between centre and end	=	943
At end	=	688
Mean value	=	897

The value of E, the modulus of elasticity, we may take as given on page 374, at 10,000 tons, which must be multiplied by 144, the dimensions here being in feet. Moreover $l = 400$, and $\mu = \frac{1112}{400}$.

The following table exhibits a comparison between the deflections computed from the above equation, and those actually observed upon the tube itself:—

	Distance from end ($=x$).	Calculated Deflection ($=y$).	Actual Deflection.
	Feet.	Inches.	
Support	0	0	0
	50	3·34	3·68
	100	6·17	6·25
	150	7·98	7·84
Centre	200	8·65	8·25
	150	7·98	7·75
	100	6·17	6·03
	50	3·34	3·9
Support	0	0	0

CHAPTER III.

THE STRENGTH AND DEFLECTION OF THE BRITANNIA BRIDGE.

Strength of the Britannia Bridge.

The strength of the Britannia large tubes, considered as independent beams, may be obtained from the simple rules employed in estimating the strength of the Conway Tube, for these tubes are nearly of uniform weight per foot throughout, although the depth is greatest at one extremity.

The Britannia Tube is nearly analogous to the Conway Tube, of which the absolute central strength has been found to be 2300 tons.

The depth of the Britannia Bridge at the middle of the span is 29 feet 3½ inches, or 27 feet 6 inches from centre to centre of the cells. The sectional area of the bottom is 585 square inches, and the distance between the bearings 460 feet. We have, therefore, for its central breaking-weight, as compared with Conway,

$$\text{(A.)} \qquad W = \frac{27{\cdot}5 \times 585 \times 400}{23{\cdot}7 \times 535 \times 460} \times 2300 = 2537 \text{ tons,}$$

and for the strain per square inch, as before, we have

$$\text{As } 2537 : \frac{1553}{2} :: 18{\cdot}6 : 5{\cdot}69 \text{ tons per square inch.}$$

Again, we may find the strain per square inch in the bottom as follows:—

The weight of the tube being 1553, we have for the strain at the centre, from its own weight (4), Ch. iii.,

$$S = \frac{388{\cdot}25 \times 230}{27{\cdot}5} = 3247 \text{ tons},$$

and

$$\frac{3247}{585} = 5{\cdot}55 \text{ tons per square inch.}$$

And again, for the strength, we have, as before,

$$\text{(B.)} \qquad \text{As } 5{\cdot}55 : 18{\cdot}6 :: \frac{1553}{2} : 2602 \text{ tons.}$$

Taking the mean of the two calculations, we have

From A	2537
B	2602
Mean central breaking-weight	2569 tons,

which is equivalent to 5138 tons equally distributed.

Similarly, for the mean per square inch from the weight of the tube itself, we have

From A	5·69
B	5·55
Mean	5·62 tons.

The central load the tube would therefore carry, or its available strength, will be

$$2569 - \frac{1552}{2} = 1792 \text{ tons},$$

or 3584 tons distributed over its whole length, or 7·8 tons per foot run, or nearly eight times as much as can come upon it, supposing it to be a single independent beam.

Thus, as regards their own weight, the Britannia Tube is a weaker beam than the Conway Tube, the strain per square inch in the latter being 4·5 tons per square inch, and in the former 5·62. The weight, however, that the Britannia Bridge would carry at the centre is 48 tons greater than the breaking-weight of the Conway Tube, viz., 1792 instead of 1744 tons, while the breaking-weight per foot at Conway is 8·72 tons, and at the Britannia only 7·8 tons. The Conway Tube is nearly a similar tube to the large model of $5\frac{1}{3}$ times its lineal dimensions, but the Britannia is not a similar tube to either of them. It is approximately 1·15 times as long, 1·15 times as deep, and 1·15 times as thick as the Conway, but instead of being 1·15 times as broad, its width is precisely the same.

If the Britannia Bridge were similar to the Conway, the central breaking-strain would be $1{\cdot}15^2 \times 2300 = 3041$ tons, instead of 2537, the sectional area of the bottom would, moreover, be $535 \times 1{\cdot}15^2 = 707$ square inches, instead of 585, and its weight would be $1112 \times 1{\cdot}15^3 = 1691$ tons, instead of 1553.

Thus its strength and weight are nearly as the lineal dimension, and the square of the lineal dimension, instead of being as the square and cube of the lineal dimensions respectively.

We should, therefore, make a greater error in calculating the strength of the Britannia, on the assumption of its being a similar tube to the model, than in the case of the Conway beam.

The sectional area of the bottom is to that of the top,

	As 585 : 648, or as 100 : 111
In the Conway Beam	as 100 : 120
In the Model	as 100 : 125

The strain tending to crush the top plates of the Britannia, is,

$$\frac{3247}{648} = 5 \text{ tons per square inch.}$$

For the breaking-weight, as regards the top, we have,

$$W = \frac{648 \times 27{\cdot}5}{460} 59 = 2503 \text{ tons,}$$

or 5006 tons equally distributed.

This breaking-weight is 66 tons less than the breaking-weight for the bottom, but the extra thickness of the plates removes any danger of buckling.

Although as independent beams the Britannia Tubes are thus more strained than the Conway Bridge, it will be hereafter seen that when continuously connected the strength of the Britannia Bridge far exceeds that at Conway. Its increase in dimensions and its unsheltered position rendered such excess advisable in a new experiment.

The strength of the small tubes is disproportionately great as compared with that of the large tubes. They were designed, not so much as beams for the mere continuation of the bridge, as for the purpose of counterpoising the large tubes, and thus their great weight became requisite.

The weight that each of these tubes would carry at the centre, in addition to the strain from their own weight, as regards the bottom, will be

C. (3) $$W = \frac{414 \times 23{\cdot}4}{230} 74{\cdot}4 - \frac{600}{2} = 2833 \text{ tons,}$$

and as regards the top,

$$W = \frac{580 \times 23{\cdot}4}{230} 59 - \frac{600}{2} = 3181 \text{ tons.}$$

Deflection of the Britannia Bridge.

The probable deflection of the large tube for the Britannia Bridge from its own weight was easily obtained from the observations at Conway. We have seen that these tubes are not similar; but they are similar in every respect except in breadth; and (disregarding the slight change in the ratio of the area of the sides to that of the top and bottom) the deflection is not altered by a change in the breadth, for the deflection is as the weight, and this quantity is constant.

The deflection of the Conway Tubes was 9 inches. Hence, for the large tube we have, by Ch. iii. 12,

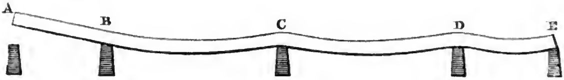
$$\text{Deflection} = \left(\frac{460}{400}\right)^2 9 = 1{\cdot}15^2 \times 9 = 11{\cdot}9 \text{ inches.}$$

A camber of 9 inches was therefore given to these tubes in their construction, to allow for the further diminution of the deflection by the effect of continuity. The actual deflection from their own weight was, as we have seen, 12·57 inches, and the mean deflection of the tubes, after being permanently fixed, remained 9·16. Hence the bottom is within $\frac{16}{100}$ths of an inch of a horizontal line.

The observations on the deflection of the tubes composing the first line, as recorded at page 672, are made with great care. The staff was placed on the vertical plates across the bottom, where permanent marks have been cut out. The instrument at the one end, and the fixed datum mark at the other, were similarly fitted on permanent marks to the castings at the side of the tube; and the table contains the mean result of a great number of midnight observations, to avoid the effect of local change of temperature, which keeps these tubes in constant motion as at Conway.

The table at page 673 illustrates the decrease of deflection by the union of the tubes longitudinally, and the subsequent lowering of the extremities. By comparing equal distances on each side of the centre, it will be seen to what extent the lowering of the neighbouring tube raised that portion near the junction in excess of the more remote portions, as might be expected.

The lowering of the land-tube A 14$\frac{5}{8}$ inches had the following effect.



1. The deflection and central strain of A B were decreased, and a strain at B was produced.

2. The centre of B C was raised 1·34 inch, and the central strain decreased, the strain at C being similarly relieved.

3. The centre of C D was lowered ·32 inch, and the central strain was increased. The strain at D was simultaneously increased.

4. The centre of D E was raised, and the strain decreased, and the weight on the tower at E increased.

Similarly, when a train enters A B, the deflection of A B is increased, of B C diminished, of C D increased, and of D E diminished. The motion is visible on the vertical cast-iron frame at E, which is inclined outwards by the action of the train, the motion being determined by a plumb-line on the frame. Thus the whole bridge sympathises with a strain at any part, and modifies its local effect; and plumb-lines at A, B, C, D, and E, are simultaneously affected, and indicate the consequent changes of deflection.

The deflection produced laterally by the wind is similarly affected, and is consequently almost imperceptible now the tubes are united, though the single tube deflected 2$\frac{1}{2}$ inches during a heavy gale.

The deflection of the land-tubes was not ascertained, as they were united to the large tubes before they were allowed to take the deflection from their own weight.

Two of the large tubes remained on temporary piers on the spot where they were constructed with a bearing of only

8 feet at each extremity during a period of several months with no alteration of deflection.

The deflection of No. 2 is only 10 inches instead of 12 inches (the mean of the three others). This anomaly can only be accounted for by the settlement of the platform, which became so distorted under the weight, that it required almost entirely to be renewed piecemeal during the construction of the tube.

The weight of one large tube between the supports is 1550 tons, distributed nearly equally throughout. The deflection from this weight being 12·57 inches, we have for the deflection per ton from a load at the centre

$$\frac{12{\cdot}57}{\frac{5}{8} \times 1550} = {\cdot}013 \text{ inch}$$

per ton, considered as an independent beam.

The breaking-weight being 1792 tons, we have the ultimate deflection in addition to its present deflection $1792 \times {\cdot}013 = 23{\cdot}3$ inches, or the whole deflection $= 35{\cdot}87$ inches.

The deflection produced by 248 tons, distributed throughout one of the large tubes, when united with the neighbouring tubes, was found to be ·67 inches, whereas the deflection from the same weight on the independent tube would have been 2 inches.

We have seen that the Anglesey Tube, C D, was first placed on its permanent bed; and, secondly, the extremity E, of the small tube D E, was raised to such a height that, after being joined at D and then lowered, a certain permanent strain was induced over the tower at D, and a similar process on lowering the large tube B C produced the requisite permanent strain at C.

The determination of the amount through which the extremities should be thus lowered to produce the required strain was a difficult problem, and this quantity had to be determined approximately at the commencement of the construction of the small tubes, as their platforms were prepared accordingly. This interesting problem will be hereafter analytically investigated.

It is at all times unsatisfactory to rely solely on theoretical deductions without the test of some tangible experiment. Many practical failures have been based on sound theory, the data only being at fault. It has, indeed, been asserted, that false facts are far more numerous and dangerous than false theories. In the construction of the Menai Suspension-bridge we find that Telford determined the lengths of his vertical suspension-rods from an experiment on a model half the size of the bridge. The strength of the tubes was, as we have seen, similarly determined from a gigantic model. The stability of the floating tube on the pontoons was confirmed by experiment, and we have recorded the experiments that were made to test the theory of the flexure of continuous beams of uniform section. It was, however, impossible in a model to imitate the conditions of the Britannia Bridge as regards deflection; and the manner in which the required degree of strain was practically obtained will be now described.

In the first place, we have to observe that the object in view was not to place the tubes in their place in precisely the same conditions as though they had been originally constructed in one length and then deposited on the towers, for in such a continuous beam (supposed of uniform section) the strain would have been much greater over the towers than at the centre of each span, whereas the section is nearly the same; the object, therefore, was to equalise the strain. The central strain, for instance, in the bottom of one independent large tube was 5·6 tons per square inch. If such a tube were now made to form part of a perfect continuous beam we should reduce the strain at the centre to 2·1 tons; whereas the strain over the centre tower would be 4·2 tons, and the strain over the land towers would be 2·8 tons per square inch; whereas the object would be to equalise the strain.

This might be done in two ways, viz. either by varying the sectional area or by varying the depth in proportion to the strain; and had the Britannia Tubes been constructed *in situ* this would have been the natural method of proceeding, but these tubes had first to be dealt with independently, and such proportions were inconsistent with their simpler form of isolated beams.

The strain was, therefore, in this case equalised, not solely by a variation of strength and depth, but principally by the amount of "tilt" given to them previous to their junction, which was, consequently, less than would have been necessary to have rendered the whole bridge a perfectly continuous beam.

Now, the deflection of a uniform beam may be measured in two ways, first, by the actual descent of the centre of the beam, where the tangent to the curve coincides with the curve itself; or, secondly, by the angle formed by the tangent at the point of support, with a horizontal line through the same point, for the curve being known, this angle is sufficient for determining the deflection; the inclination of the vertical extremity of the beam, moreover, evidently gives this angle.

We have already seen how this inclination was observed by means of the deflection instrument at Conway.

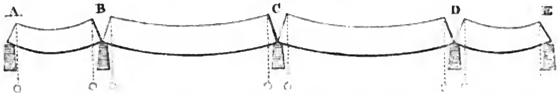
Previous to the removal of the platform from beneath the finished tubes at the Straits, plumb-lines were suspended for the same purpose at each extremity, and the inclination of the vertical from the effect of deflection was then determined.

The plumb-lines were 20 feet long, or 240 inches. Their inclination at each extremity was found to be alike, and as follows :—

	Inches.		
Tube No. 1	1·25	or	$\frac{1 \cdot 25}{240}$
— 2	1·25	or	$\frac{1 \cdot 25}{240}$
— 3	1·31	or	$\frac{1 \cdot 31}{240}$
Mean......	1·27	or	$\frac{1 \cdot 27}{240}$

Tube No. 4 was not observed.

Now, if we suppose A E to represent the Britannia Bridge, constructed in one length on a level platform, and when complete to be cut through at the dotted lines, and each portion allowed to take its own deflection, the tubes would take the following form, which is the form in which they reposed on their separate temporary piers.



The angles measured by the plumb-lines are the angles of separation of the vertical extremities of the tubes. Consequently, in order to restore these separate tubes to their original condition, C D being supposed to be first permanently placed, we have first to raise the extremity E through an angle equal to the two observed angles of inclination at D; and having united the tubes in this position, to lower the extremity E back again to its bed, the angle at C will then be lessened; and the extremity B has now to be raised through an angle equal to the diminished angle at C, and being thus united and lowered, a similar operation with A would restore the whole line to its original position.

In this manner, by actual observation, the required conditions in the Britannia Bridge were obtained; the spaces through which the tubes were lowered being rather less than would be requisite for perfect continuity, to equalise more nearly the strain at the centre and in the towers.

Thus, disregarding the deflection of the small tube, the extremity E would require to be raised $\frac{1{\cdot}25}{240} \times 2760$ inches $= 14{\cdot}4$ inches. This tube was actually raised 14⅝ inches. On being lowered, the plumb-lines at D moved $\frac{{\cdot}625}{240}$, while the observed return of the plumb-line at the farther extremity C was $\frac{{\cdot}2}{240}$.

Consequently B should be raised $\frac{2{\cdot}5 - {\cdot}2}{240} \times 5520 = 52{\cdot}9$ inches. This would have produced too much tension over the Britannia Tower. The actual rise was 31·5 inches.

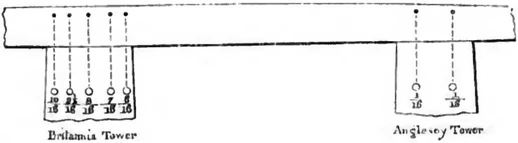
The actual extension in the top of the tube through the Britannia Tower, produced by the lowering of the extremity B, was now ascertained by means of rods laid on the top of the tube.

A length of 20 feet was found to be stretched ·125 inch, or $\frac{1}{1920}$ of the length.
A length of 50 feet .... ·281 inch, or $\frac{1}{2135}$ —

The mean extension was $\frac{1}{2027}$ of the length.

The strain in tons per square inch would thus appear to be $\frac{10000}{2027} = 4{\cdot}9$ tons per square inch; but it must be remembered that in the actual lines of junction the section was unavoidably less than that of the tube itself. The extension was consequently increased in amount from this cause, and the strain per square inch in the tube itself is, therefore, less than the above quantity; this strain was, moreover, subsequently diminished by the lowering of the land-tube A.

The motion of the plumb-lines in the Britannia Tower C, and at the land tower D, on lowering the tube B C, is shewn below.



In a similar manner the tube A B was lowered through a space of 14⅝ inches, and thus the strain per square inch throughout the bridge, as approximately as it can be obtained, was ultimately as in page 785.

APPLICATION OF GENERAL ANALYTICAL FORMULÆ TO THE BRITANNIA BRIDGE.

This case presents considerable difference from that of the Conway Bridge, on account of the *continuity* of the five tubes forming the length of the whole. We shall first investigate the strength and deflection of one of the large spans treated as an independent tube, and shall then proceed to consider the effect of the continuity.

Strength of the large Tube of the Britannia Bridge, considered as an Independent Beam.

This is found precisely as in the case of the Conway Tube on page 755, from the equation—

$$\frac{\mu l}{f} = \frac{8}{c l} \mathrm{I}.$$

The value of I for the centre of the tube is found from the same equation as before, viz.—

$$I = \left(a_1 + \frac{a_3}{3}\right) h_1^2 + \left(a_2 + \frac{a_4}{3}\right) h_2^2,$$

for which we have the following values—

a_1 .... = 4·07 square feet.
a_2 .... = 4·5 „
a_3 .... = 1·1 „
a_4 .... = 1·0 „
h_1 .... = 14·3 „
h_2 .... = 13·16 „

Hence,

I .... = 1746.

Proceeding as before—

$$\frac{\mu l}{f} = \frac{30{\cdot}4}{c}.$$

To find the strain from the weight of the tube itself, we have, for the bottom plates,

$$\frac{1553}{f} = \frac{30{\cdot}4}{15{\cdot}3},$$

or

$$f = 784 = 5{\cdot}45 \text{ tons per square inch.}$$

For the top plates,

$$\frac{1553}{f} = \frac{30{\cdot}4}{14},$$

or

$$f = 718 = 5 \text{ tons per square inch.}$$

To find the breaking-weight of the tube, we have, first, as regards the bottom plates,

$$\frac{\mu l}{2678} = \frac{30{\cdot}4}{15{\cdot}3},$$

or

$$\mu l = 5320 \text{ tons.}$$

As regards the top plates,

$$\frac{\mu l}{2131} = \frac{30{\cdot}4}{14}$$
$$= 4628 \text{ tons.}$$

The mean of these is 4974 tons, being a close approximation to the strength previously obtained in a different manner.

Deflection of the large Tube of the Britannia Bridge as an independent Beam.

We will confine the computation of the deflection of this tube to that at the middle of its length, which is obtained from Equation XL., page 274, viz. :—

$$D = \frac{5 \mu l^4}{384 \, E \, I}.$$

The value of I, the moment of inertia, is not constant throughout the length, and we must therefore take a mean value. This will be obtained from the different values of the moment of inertia in the manner previously adopted for the Conway Bridge.

Values of I, *the Moment of Inertia, for the large Tube of the Britannia Bridge.*

At land tower .... = 1132
Half-way between land tower and centre .... = 1520
At centre of tube........................ = 1746
Half-way between centre and Britannia Tower = 1664
At Britannia Tower .... = 1857
Mean value .... = 1584

The above equation gives, therefore,

$$D = \frac{5 \times \frac{1553}{460} \times 460^4}{384 \times 1{,}440{,}000 \times 1584} = 0{\cdot}85 \text{ feet},$$

or

$$= 10{\cdot}2 \text{ inches}.$$

The observed deflections of the four tubes when the platforms were removed from under them, varied from 10 inches to 11·78 inches, the mean of the whole being 10·97.

The experiments tried on the tubes when they first took the deflection from their own weight, furnish another and very elegant means of comparison between theory and observation, in reference to the deflection. It has been explained on page 768 that the angular motion of each end of the tube, when the platform was removed from under it, was carefully measured by a plumb-line 20 feet long; each end being found to move through an angle of which the tangent was about $\frac{1·27}{240}$, or $= 0·0053$, corresponding with an angle of about 0° 18½′.

Now, a little consideration will make it evident that this angle, moved through by the plumb-lines, is equal to the inclination of the deflection curve to the horizontal at the end of the tube, which may be ascertained theoretically in the following manner. In the equation on page 273—

$$\mathrm{E\,I}\frac{dy}{dx} = \frac{\mu}{2}\left(\frac{x^3}{3} - \frac{l\,x^2}{2} + \frac{l^3}{12}\right)$$

$\frac{dy}{dx}$ represents the tangent of the inclination between the deflection curve and the horizontal, at any point distant x from the end. If, therefore, we make $x = 0$, and represent the inclination at the end of the tube by α, we have—

$$\mathrm{E\,I}\tan\alpha = \frac{\mu\,l^3}{24},$$

or

$$\tan\alpha = \frac{\mu\,l^3}{24\,\mathrm{E\,I}}.$$

Substituting, therefore, the proper values of the quantities in this equation, we obtain—

$$\tan\alpha = 0·006,$$

or

$$\alpha = \text{about } 0° \; 20\tfrac{1}{2}',$$

agreeing tolerably well with the observed value as given above. This determination will hereafter be made use of in treating of the continuity.

STRENGTH AND DEFLECTION OF THE BRITANNIA BRIDGE CONSIDERED AS A CONTINUOUS BEAM.

We now proceed to take into account the *continuity* of the Britannia Bridge, which considerably modifies the results arrived at by treating each span as a single beam independent of the others.

In Section III., chapter 4, page 288, we have given an investigation of the case of a beam of five spans, making the two outer ones half the breadth of the two inner ones, in order to assimilate the investigation in some measure to the case of the Britannia Bridge. This investigation determines the strength and deflection of a beam whose weight and moment of inertia are uniform throughout its length, and whose continuity is perfect; and if the Britannia Bridge fulfilled these conditions we might apply to it the formulæ there deduced, without further trouble.

This, however, is not the case; neither the weight nor the moment of inertia is uniform, nor is the continuity perfect. It will be necessary to examine these peculiarities, and to modify the processes of investigation in accordance with them.

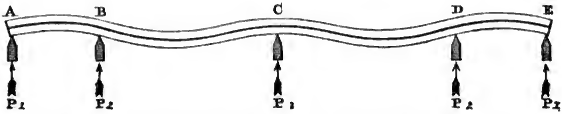
In the first place, the weight is not uniform throughout the length; the average weight per lineal foot of the large tubes is 3·38 tons, while that of the small, or land tubes, is only 2·6 tons. It will be necessary to make an allowance for this difference.

Secondly, the moment of inertia, which in the former investigation is supposed uniform throughout the whole length of the beam, is considerably less in the small than in the large spans; that of the latter has already been determined, = 1584; that of the former is found by a similar process, taking the average of three determinations, at the middle and the two ends, = 962.

Thirdly, it will be necessary to inquire how far the tube, as actually erected, corresponds with the conditions of perfect *continuity* throughout its length. A perfectly continuous beam, such as is treated of in Section III., chapter 4, may be supposed to have been originally made in one connected length, perfectly straight, and then to have been placed bodily upon the supports destined to bear it. Such, however, it is almost needless to state, could not be done with a beam like the Britannia Tube; it was made in four separate lengths, each placed in the first instance as an independent beam over its proper opening, and the whole then connected together by riveting at the junctions. It has been explained by what means the effect of continuity was produced; namely, by first raising the end of one independent tube, and then lowering it back again after its opposite end had been joined to the adjacent tube: it will be necessary to examine in each case how nearly the effect of this operation approximated to that of perfect continuity; and if it is found in any case to fall short of this, the formulæ must be modified accordingly.

Let A B C D E, fig. 1, represent the Britannia Tube.

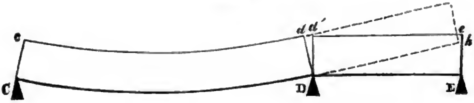
Fig. 1.



The first junction made was at D, between one of the large and one of the small tubes. The latter tube, D E, was built in its place with the end E raised above its support; the long tube, C D, being then put in its place, and having taken the position due to it as an independent tube, the junction was effected by riveting at D, and the end E then lowered down upon the abutment. The question now to consider is, how much ought the end E to have been raised in order to put the two tubes, when riveted together, and the end E lowered, in the condition of one continuous tube?

In fig. 2, let C D represent the long tube deflected by its own weight as an independent beam, and D E the short tube in the position it would occupy if built upon a straight platform in its normal or horizontal position; and for the sake of facilitating the explanation of their movements, we will suppose the ends D *d′*, D *d*, C *c*, E *e*, cut off perfectly square* with the neutral lines of the respective tubes.

Fig. 2.



Now, in order to put these tubes into a position of continuity, *i. e.* to bring them into the same state as if they had been constructed together in one straight line, it will be necessary to raise the end E so as to make the two faces D *d* and D *d′* coincide, and then to join these two ends together, *i. e.* to move the whole small tube, round D as a centre, through an angle = *d* D *d′*, or which is the same thing, = E D *h*. But it is evident that the angle *d* D *d′* is pre-

* This was not so in reality, as a junction-piece was introduced between the tubes; but the principle applies equally well, however the junction be made, as it involves merely the positions of the *neutral lines* of the tubes.

cisely the angle through which the end of the large tube will have moved, in deflecting by its own weight from a horizontal position, which angle we have designated at page 773 by the symbol α, and the value of which is there determined both by computation and experiment. We have, therefore, $\angle$ E D h = α, or,

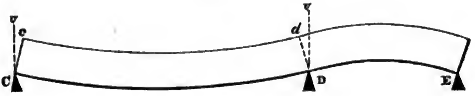
$$\frac{\mathrm{E}\,h}{\mathrm{E\,D}} = \tan\alpha = 0{\cdot}0053.$$

Whence E D being = 230 feet, we have E h = 1·219 feet, or $14\frac{5}{8}$ inches, *i. e.* the end E should have been raised $14\frac{5}{8}$ inches before the junction, in order to give the perfect condition of continuity. Now, this is the amount it actually was raised, therefore we may assume that, as far as this junction is concerned, the tube has been made perfectly continuous.

But it is desirable to inquire further what ought, according to theory, to be the new position of the tube when thus united, on the end E being lowered down to its support; or, in other words, we have to investigate the conditions of the continuous tube C E, supported on three points at unequal distances C D E.

This may be done as follows:—

Fig. 3.



Let

D E = l = 230 feet; then C D = $2\,l$ = 460 feet,
μ = load per lineal foot on the span C D; = 3·38 tons,
μ_2 = that on the short span D E; = 2·6 tons.

Then,

$\mu_2\,l$ = weight of short span = 600 tons,
$2\,\mu\,l$ = weight of long span = 1553 tons.

Let

I = moment of inertia of long span = 1584,
I_2 = that of short span = 962.

Also, for this portion of the investigation, let—

p_1 = resistance on support E,
p_3 = that on C,
β = inclination of neutral line to the horizontal over support D.

Proceeding on the principles adopted in the discussion of continuous beams, Section III., Chapter 4, we find, for the large span,

$$E\,I\,\frac{d^2 y}{d\,x^2} = \frac{\mu\,x^2}{2} - p_3\,x.$$

Integrating, and remembering that at the point D, where $x = 2\,l$, $\frac{d\,y}{d\,x} = \tan\beta$, we have—

$$\text{(LXVII.)}\quad E\,I\,\frac{d\,y}{d\,x} = \frac{\mu}{6}\,x^3 - \frac{p_3}{2}x^2 - \frac{4}{3}\,\mu\,l^3 + 2\,p_3\,l^2 + E\,I\,\tan\beta.$$

Integrating again, and substituting in the resulting equation the corresponding values of $x = 2\,l$ and $y = 0$, we obtain—

$$\text{(LXVIII.)}\qquad E\,I\,\tan\beta = \mu\,l^3 - \frac{4}{3}\,p_3\,l^2.$$

By a similar process we obtain from the small span—

$$\text{(LXIX.)}\qquad E\,I_2\,\tan\beta = \frac{1}{3}\,p_1\,l^2 - \frac{1}{8}\,\mu_2\,l^3.$$

Now, by equality of moments round D, we have—

$$\text{(LXX.)}\qquad p_1\,l + 2\,\mu\,l^2 = 2\,p_3\,l + \frac{1}{2}\,\mu_2\,l^2.$$

Eliminating, therefore, between the three last equations, we find the following values—

p_1 .... = 53 tons,

p_3 .... = 653

$\tan \beta$ .... = 0·00216.

The results of this investigation may be compared with what actually took place when the tube was lowered. A plumb line 20 feet long, being suspended at the junction D, was observed, when the tube was lowered, to move through $\frac{5}{8}$ths of an inch, being equivalent to an angle whose tangent was $\frac{\cdot 625}{240}$, or 0·0026.

Now, this angle would evidently represent the difference between the angle α (*i. e.* inclination of the end of the long tube *before* the junction $= d\,\mathrm{D}\,d'$, fig. 2); and the above-mentioned angle $\beta = d\,\mathrm{D}\,v$, fig. 3, the inclination of the continuous tube at that point *after* the junction. We nave, therefore, the theoretical value of this angle, taking the tangents of these small arcs to represent the arcs themselves,

From Angle α .... = 0·0053

Deduct Angle β .... = 0·00216

Tan. Angle, which should have been moved through by plumb-lines at D, according to theory .... = ·00314

which does not much differ from the actual angle observed.

A similar plumb-line was also suspended at C, and this was observed, after the junction, to move through ·2 inch, or through an angle whose tangent was $= \frac{\cdot 2}{240}$, or 0·00083, which would reduce the previous angle of inclination of this end of the tube ($= \alpha$) to ·0053 − ·00083, or = ·00447.

This residuary angle ($= c\,\mathrm{C}\,v$, fig. 3), which we will represent by θ, may be computed theoretically as follows.

In Equation LXVII., $\frac{dy}{dx} = \tan \theta$, when $x = 0$; *i. e.*,

$$\mathrm{E\,I} \tan \theta = \mathrm{E\,I} \tan \beta + 2\,p_3\,l^2 - \frac{4}{3}\,\mu\,l^2,$$

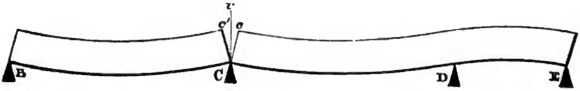
from which we find—

$$\tan \theta = 0{\cdot}0041,$$

which nearly agrees with the angle observed.

We now proceed to consider the junction effected over the centre or Britannia Tower C.

Fig. 4.



Let C D E, fig. 4, represent the large and small tube previously joined at D into one continuous tube, and B C, the other large tube, which it was proposed to join on to the former at C. Supposing, as before, the lines C *c* and C *c′* to represent the ends of the tubes, it is evident that in order to produce the effect of continuity, the end B of the tube C B ought to be raised until the lines C *c′* and C *c* coincide; *i. e.* through an angle $= c' \mathrm{C} v + v \mathrm{C} c$. But $c \mathrm{C} v = \alpha$, and $v \mathrm{C} c = \theta$, whence, taking the tangents to represent the arcs themselves,

Tan α	=	·0053
Tan θ	=	·00447
Tan angle through which the tube should be raised	=	·00977

But C B being 460 feet, the height to which the end B should be raised will be $= 460 \times 0{\cdot}00977 = 4{\cdot}5$ feet. Now, we find that it was actually raised 2 feet $7\frac{1}{2}$ inches, or 2·625 feet, so that at this junction the tube has *not* been made continuous. It was not, in fact, intended to make the continuity perfect at this point, for the following reason. It will be seen by a reference to page 290, that in a continuous beam the strain over the support C is to that in the centre of the long span as 6 to 3; now the object sought in making the centre connexion of the Britannia Bridge, was, to make these strains about *equal*, it being anticipated that this effect would be produced by giving an imperfect degree of continuity at this point. We shall see hereafter that this desired result has been approximated to.

It will be observed, that the degree in which the continuity falls short of being perfect at this point of junction is measured by the magnitude of the angle $c\,C\,c'$, remaining open after the end B of the tube was raised, this angle expressing, moreover, the inclination to each other, at B, of the neutral lines of the two tubes, which lines ought, if the tube were perfectly continuous, to coincide at that point. Let this angle $= 2\,k$, k being thus made to represent the inclination of one of the neutral lines to the horizontal after the tube is connected throughout. We shall then have (the arcs being very small)—

$$\tan 2\,k = \cdot 00977\,\frac{2\cdot 625}{460},$$

or

$$\tan 2\,k = \cdot 00407,$$

or

$$\tan k = \cdot 002035.$$

We shall hereafter use this as the measure of the imperfect continuity.

The third and last junction made was that at B; the calculation of this would be very complicated, but we are justified in assuming that the tube was made perfectly continuous at this point.

Finally, therefore, it appears that the tube may be considered as made continuous at B and D, but falling short of perfect continuity at C by a certain known amount. We shall accordingly proceed with the investigation on these conditions.

Retaining the symbols l, μ, μ_2, I, I_2, and E, as before, let P_1 represent the resistance or re-action on the supports at A and E, P_2 that at B and D, and P_3 that on the centre support C. Also let β represent the inclination of the deflection curve to the horizontal, over the support B or D.

From the curve of the small span A B we have, by the same process of investigation as on page 286, Equation LV.,

$$\text{(LXXI.)} \qquad E I_2 \tan \beta = l^2 \left(\frac{1}{8} \mu_2 l - \frac{1}{3} P_1 \right).$$

Proceeding in a similar manner for the portion B C of the curve, we obtain—

$$\text{(LXXII.)} \quad E I \tan \beta = l^2 \left(\frac{2}{3} P_2 + \frac{5}{3} P_1 - \frac{1}{3} \mu l - \frac{7}{6} \mu_2 l \right)$$

The continuity being imperfect over the centre support C, where the inclination of the neutral line to the horizontal is $= k$, make $\frac{d y}{d x} = - \tan k$ at that point (taking the negative sign as y is then decreasing), whence, by substitution in the differential equation, we have

$$\text{(LXXIII.)} \quad E I \tan \beta = l^2 \left(- K + 2 P_2 + 4 P_1 - \frac{4}{3} \mu l - 3 \mu_2 l \right),$$

where K is used for abbreviation to express the quantity,

$$\frac{E I}{l^2} \tan k.$$

Eliminating between Equations LXXI., LXXII., and LXXIII., and making $i = \frac{I}{I_2}$,

$$P_1 = \frac{\frac{3}{4}(2 + i)\,\mu_2 l - \mu l - 3\,K}{3 + 2\,i}$$

$$P_2 = \frac{\left(3 + \frac{23}{8}\,i\right)\mu_2 l + (8 + 3\,i)\,\mu l + 3\,(5 + i)\,K}{2\,(3 + 2\,i)}$$

Also, since $2\,P_1 + 2\,P_2 + P_3 = 4\,\mu l + 2\,\mu_2 l$,

$$P_3 = \frac{(6 + 5\,i)\,\mu l - \frac{3}{8}\,i\,\mu_2 l - 3\,(3 + i)\,K}{3 + 2\,i.}$$

Substituting the numerical values of the quantities, and taking

$$i = \frac{I}{I_2} = \frac{1584}{962} = \frac{5}{3} \text{ nearly,}$$

and

$$K = \frac{E\,I}{l^2}\tan k = 88,$$

we find the pressures on the supports as follow:*—

Pressure on support A = P_1..........	=	96 tons.
„ „ B = P_2..........	=	1305 „
„ „ C = P_3..........	=	1504 „
„ „ D = P_2..........	=	1305 „
„ „ E = P_1..........	=	96 „
Total weight of tube between supports ..		4306 tons.

In investigating the *strength* of the tube, in its continuous state, we shall confine ourselves to the *strains* at three points, viz. 1st, Over the support B or D; 2d, In the centre of the large span; and 3d, Over the centre pier.

1st. Over the support B or D. Let φ represent the sum of the moments of the elastic forces at this point of the beam; then, applying the principle of the equality of moments to the portion A B of the beam,

---

* These are the pressures due only to the weight of the tubes between the supports; the actual pressures are somewhat increased by the weight of the portions over the towers. The small amount of pressure on the abutments was verified by observation.

$$\Phi = \frac{1}{2} \mu_2 l^2 - \mathrm{P}_1 l;$$

but by Equation I. (page 244) $\phi = \frac{f}{c} \mathrm{I}$; therefore

$$\frac{f}{c} \mathrm{I} = l \left(\frac{1}{2} \mu_2 l - \mathrm{P}_1 \right) = 46920.$$

Now, at this part of the beam the value of I is = 1132. Also, for the top-plates c = 10·9, and for the bottom-plates c = 16·1; whence, substituting the numerical values in the above equation, we find the values of f, which will be given in the table below.

2. At the centre of the long span B C, a similar application of the principle of equality of moments, gives—

$$\Phi = 2\,\mathrm{P}_1 l + \mathrm{P}_2 l - \frac{1}{2} \mu l^2 - \frac{3}{2} \mu_2 l^2,$$

or,

$$\frac{f}{c} \mathrm{I} = l \left(2\,\mathrm{P}_1 + \mathrm{P}_2 - \frac{1}{2} \mu l - \frac{3}{2} \mu_2 l, \right) = 48070.$$

In this case I = 1746; and c is for the top-plates = 14; for the bottom-plates = 15·3.

3. Over the centre support C, here—

$$\Phi = 2 \mu l^2 + \frac{5}{2} \mu_2 l^2 - 3\,\mathrm{P}_1 l - 2\,\mathrm{P}_2 l,$$

or,

$$\frac{f}{c} \mathrm{I} = l \left(2 \mu l + \frac{5}{2} \mu_2 l - 3\,\mathrm{P}_1 - 2\,\mathrm{P}_2 \right) = 35650,$$

where I = 1857, and c for the top-plates = 14·6, for the bottom-plates = 15·4.

Computing the above, we arrive at the following results:

Strains upon the Britannia Bridge Tube from its own weight (or Values of f).

	Strain on Top Plates.	Strain on Bottom Plates.
	Tons per square inch.	Tons per square inch.
Over land-towers B and D	3·1	4·6
At middle of large span	2·7	2·9
Over centre, or Britannia Tower....	2·0	2·1

It will thus be seen that the object sought in effecting the junction of the tubes, viz., to throw nearly an equal strain on the two latter named points, has been approximated to.

The equation for the *deflection* of the large tube is,

$$\mathrm{E\,I}\,y = \frac{\mu}{24}\,x^4 + \frac{\mu_2\,l - \mathrm{P}_2 - \mathrm{P}_1}{6}\,x^3 + \left(\frac{\mu_2\,l^2}{4} - \frac{\mathrm{P}_1\,l}{2}\right)x^2 + \mathrm{E\,I}\tan\beta\,x.$$

Making $x = l$, the deflection in the centre is computed $= 4{\cdot}68$ inches.

Now, it must be recollected that between the time when the tubes were first allowed to take their own weight and their permanent junction in the towers, their deflection was found to increase considerably; so that before they were finally joined, the centre deflection, instead of being 10·2 inches (the amount due to the tube according to theory), had become 12·57 inches. This increase of 2·37 inches may be looked upon as a *permanent set*, probably caused by the violent strains to which the tube was subjected during the operations of floating and raising, and which must in consequence influence, by its whole amount, the deflection when the tube was permanently joined. Adding, therefore, this permanent set, we obtain 7·05 inches for the calculated deflection of the continuous tube. The actual deflection, as observed, was 9·16 inches. The difference may probably be accounted for by the diminution of strength in the junctions over the towers. It has already been shewn that the extension at these parts was observed to be much greater than that due to the strain, and the consequence of this must naturally be an increased deflection at the centre of the tube. It must also be recollected that we have assumed the moment of inertia to be uniform throughout the length, which is not strictly the case; the unequal distribution of the material is, probably, an additional cause of variation in the deflection.

The *points of contrary flexure* in the long span are computed by the equation,

$$\frac{\mu}{2} x^2 + (\mu_2 l - P_1 - P_2) x = \left(P_1 - \frac{\mu_2 l}{2}\right) l,$$

the two roots of which give the points of contrary flexure,

54 feet from the Britannia Tower,
68 feet from the land tower.

It is possible that these may be slightly altered by the same circumstances which affect the deflection.

STRENGTH OF THE TUBE TO RESIST THE LATERAL FORCE OF THE WIND.

The Britannia and Conway Bridges being, from their exposed situations, subject to the frequent action of violent winds, it is desirable to ascertain what is their strength to resist pressure in a *lateral* direction. We shall confine our inquiry to the determination of the strength of the long tube of the Britannia Bridge considered as an independent beam, disregarding the stiffening effect of the continuity.

It will be evident, on a little consideration, that the tube, when subjected to lateral pressure, may be represented by a flanged girder, of which the usual top and bottom flanges correspond to the sides of the tube, the vertical rib corresponding to the sum of the top and bottom. Now, since the two sides are of equal area, the strength of this form of girder is expressed by Equation XXIX., page 257,—

$$\frac{\mu\, l}{f} = \frac{8\, d}{l}\left(a + \frac{a'}{6}\right),$$

where $\mu\, l$ will represent the total force of the wind distributed equally over the side face, l the length of the tube, d its *breadth*, a the area of one side, and a' the sum of the areas of the top and bottom.

Taking the mean dimensions of the large tube, we have—

$$\begin{aligned} l &= 460 \\ d &= 14\cdot \\ a &= 1\cdot 25 \\ a' &= 7\cdot 81 \end{aligned}$$

from which quantities—

$$\frac{\mu\, l}{f} = 0\cdot 621.$$

Now, a violent storm exerts a force of about 20 lbs. on every square foot of surface exposed to its direct action. Taking, therefore, the side surface of the tube at about 13,400 square feet, we have $\mu\, l = 120$ tons; whence $f = 74\cdot 5$ tons per square foot; that is, the greatest strain caused by a violent storm blowing directly on the side of the tube, is about *half a ton* per square inch, an amount scarcely worth notice.

LIMITS OF SIMILAR BEAMS.

We have alluded in a previous chapter to the theoretical limits as to the magnitude of similar beams. We may observe generally:

Since the weight of similar solids is as the cube of their like lineal dimension, any similar tube which is n times larger than the other, will be n^3 times as heavy, and with respect to its transverse strength will be n^2 times as strong.

And as regards the limit at which any tube would just break with its own weight: as we increase any tube n times in lineal dimension, the ratio of the breaking-weight to the weight of the tube itself varies as $\frac{n^2}{n^3}$, or as $\frac{1}{n}$, or inversely as the lineal dimensions. Hence this important practical result. If the weight of any tube is $\frac{1}{2}$, or $\frac{1}{3}$, or $\frac{1}{n}$th of its breaking-weight, a similar tube made twice or three times, or n times the same size respectively, will just break with its own weight.

Thus, if the breaking-weight of any tube be three times its own weight equally distributed, a similar tube of three times the same dimensions would just support itself.

Again, if we take any given model and enlarge it to twice, three times, four times, n times the same lineal dimensions, n being of such a magnitude that the tube will just fail from its own weight, the tube in this series which will bear the greatest weight per foot run will be the tube corresponding to the number $\frac{n}{2}$. The strain on the bottom of such a tube will be also equal to one-half the ultimate tensile strength of the material.

By easy applications of formula XXIII., page 256, we find the following limits for the Britannia large tube:—

If the dimensions of the section remained constant and the length only were increased, the tube would break with its own weight when it became about 850 feet long.

But if the dimensions of the section were also increased, so that the tube retained the same proportions, becoming then a *similar* tube to what it is at present, it would break with its own weight when it became about 1570 feet long. The depth of the tube would in this case be 100 feet, the breadth 48 feet, and the weight 62,000 tons.

Other curious properties of similar tubes may be determined from the preceding reasoning; but in practice these theoretical limits cannot be approached. The impossibility of construction, the rapid increase in the weight of the requisite pillars for any great extension of depth, the necessary additions for preserving the general form of a large structure, considered merely as an edifice, independent of its action as a beam, and the great crushing strain to which the bearings would be subjected, are all elements increasing in a high ratio with the dimensions, and rendering impossible, on similar principles, any structure of much greater magnitude than the Britannia Bridge. This will be evident if we call to mind that in that tube twenty-one per cent of the whole weight of the sides is already consumed in stiffening them; and not only would the weight of a larger structure increase as the cube of its length, but it would also require a much larger percentage of stiffening plates in the sides, for as the pillars increase in height the weight increases as the cube of the length, while the strength is only as the square.

In this respect the ordinary suspension-bridge possesses considerable advantages over other structures, for the strain being wholly tensile, the laws of pillars do not come into operation, and such bridges may be safely constructed of magnificent dimensions with little material.

These advantages, however, at once disappear when the horizontal strain is resisted by a pillar forming a portion of the structure itself, as in the case of the Chepstow Bridge, p. 102; and the limits of such a system are nearly similar to those of a tube, the weight per foot run increasing nearly as the square of the length, and, therefore, the weight of the whole structure as the cube.

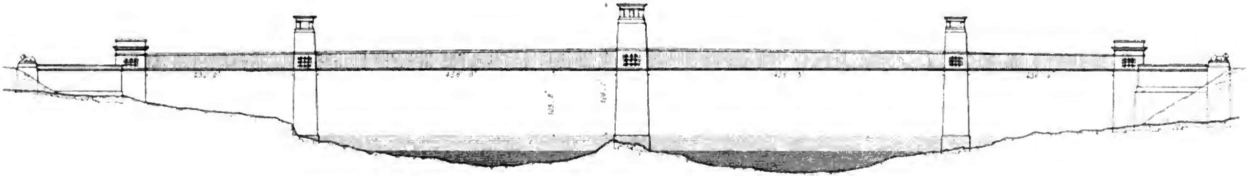
The magnitude of the arch is limited, like that of the beam, by the danger of distortion, its stability being dependent on the laws of pillars; the thrust on the abutments becomes, moreover, a formidable difficulty in arches of great magnitude.

For the purpose of comparison we have engraved, in the the accompanying plate, the Britannia Bridge, the High Level Bridge, Newcastle, and the Southwark Bridge, London, to the same scale. The Southwark Bridge being well known, forms a convenient unit for comparison; and when it is remembered that these arches are the largest in existence, the magnitude of the Britannia Bridge becomes more striking, and the difficulty of adopting any other principle of construction for the crossing of such a chasm becomes more apparent.

The High Level Bridge is remarkable for its double roadway, the top being used for railway purposes, while the suspended platform at the springing of the arches forms a road for public traffic. The thrust of the arches is resisted by horizontal ties of wrought-iron, so that any settlement in the piers may not disturb the equilibrium of the arches. This precaution was the more requisite as the foundations were extremely bad. The cost of this elegant viaduct was as follows:

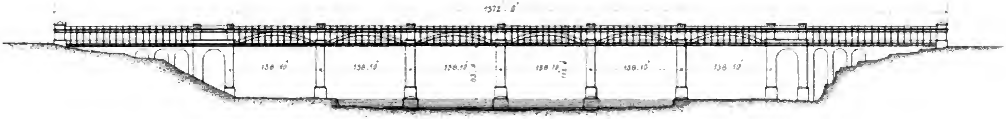
To face P. 790.

BRITANNIA TUBULAR BRIDGE

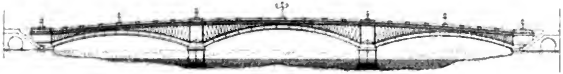


HIGH LEVEL BRIDGE

Newcastle.



SOUTHWARK BRIDGE



	Ashlar. Cubic feet.	Rubble. Cubic feet.	Concrete. Cubic feet.
Masonry in piers	321,387	23,678	46,224
Do. in land arches of approaches	360,222	92,718	,,
Total..........	681,609	116,396	46,224

Weight of cast-iron in the whole	4728½
Do. of wrought-iron	321½
Total	5050 tons.

Cost of masonry, including coffer-dams, &c. &c. ..	£120,000	0	0
Do. of iron-work, including road and railway, entrances, gates, &c.	114,450	0	0
	£234,450	0	0

The weight of the iron-work is thus about 6 tons per foot run, and the cost about *22l.* per ton; while the weight of the iron-work on the Britannia Bridge is only 7·5 tons per foot run. Indeed, if we take into account the magnitude of the span, and compare the cost with that of any other structure enlarged to the same dimensions, we shall find the Britannia Bridge equally remarkable, whether we consider its economy, its weight, its practical advantages in construction, or its unprecedented magnitude.

SECTION IX.

THE TIDES.

The phenomena of the tides, in their daily ebb and flow through the Menai Straits, became of prominent interest in connexion with the critical operation of removing the tubes from the site of their construction to the base of the towers; the daily progress of the work was, moreover, immediately dependent on their condition, and the accurate prediction of their heights and periods was from the first an object of much importance.

The great tidal wave in its passage up the Channel is intercepted by the Island of Anglesey; and while the great body of the wave makes a circuit of about sixty miles round the island, a smaller portion takes the shorter route through the Straits, a distance of about eighteen miles;—the difference between the times of high-water at Carnarvon and Beaumaris, the two extremities of the Straits, being about one hour.

Before tracing the progress of a tide through the Straits it will be necessary to have a clear idea of the nature of the locality. Carnarvon is situated near the south-west extremity of the Straits, and is separated from the sea by an extensive mass of shifting sand-banks, at a distance of four or five miles, termed the Carnarvon Bar, which are not navigable at low-water; and so heavy a sea breaks over them during south-westerly gales, that no vessel dares approach them.

About six miles from Carnarvon is the Britannia Bridge, its centre pier founded on the Britannia Rock; and a mile farther on is the Menai Suspension-bridge. The channel between the two bridges is much contracted, and almost closed, by a number of islands and sunken rocks, called the Swellies, through which, in certain states of the tide, the water rushes with great noise and violence, forming innumerable eddies, and rendering the navigation extremely difficult and dangerous. It is here that the tide-wave meets with its principal obstruction, which is so great, that while the time of high-water at the Britannia Bridge coincides nearly with that at Carnarvon, the time at the Menai Bridge, only one mile distant, is an hour later, and is almost coincident with that of Beaumaris.

Four miles farther on is Beaumaris, which is situate at the north-east extremity of the Straits, and, like Carnarvon, is separated from the open sea by an immense area of sandbanks, called the Lavan Sands, which are mostly dry at low-water. There remains, however, a narrower channel, with ample depth of water for the passage of vessels at all states of the tide. The general appearance of the Straits between Carnarvon and Beaumaris is that of a broad and stately river, with fertile and well-wooded banks, studded with houses and villas.

There are two phenomena connected with the transit of a tide which are very generally confounded with each other,—one is, the time at which the water becomes stationary, preparatory to a change in its direction—this is commonly, but erroneously, considered as high or low-water; and the other is the real high or low-water in relation to the actual level of the tide. And since at the Menai Straits these phenomena are by no means concurrent, it is necessary to distinguish them carefully, calling the one *tide-turn*, or *slack-water*, and the other HIGH OF LOW-WATER.

We will now trace the progress of an ordinary tide through the Straits, commencing at the moment of low-water at Carnarvon. The same description would suffice for all other tides, altering only the heights.

At that moment the tide has entered the Straits, and been flowing towards the Britannia about fifteen minutes, which it continues to do for about five hours and a quarter longer, until it gradually slackens and becomes stationary, first at the Menai Bridge, six minutes afterwards at the Britannia, and in ten minutes more at Carnarvon; the tide then commences to ebb in the opposite direction, flowing out of the Straits at Carnarvon. In the meantime, the main tide-wave has travelled round the island, and has been entering the Beaumaris end of the Straits for three hours; and although it is yet an hour and a quarter before high-water at Beaumaris, yet sufficient water has already flowed through the more open channel of Beaumaris to out-top and reverse the Carnarvon tide.

Twenty minutes after the tide has commenced to ebb at Britannia is the time of high-water there, and in ten minutes more it is high-water at Carnarvon;—the tide-turn in both cases preceding the high-water by twenty minutes, and both phenomena occurring at the Britannia ten minutes earlier than at Carnarvon.

We have already seen that the tide becomes stationary at the Britannia nearly as soon as at the Menai; but the case of high-water is very different: the tide continues to flow in from Beaumaris in such quantity that the water rises at the Menai Bridge for nearly an hour and a half after the tide has turned, notwithstanding the volume that pours through the Swellies, and the now rapidly falling tide at the Britannia. At this time the difference of level between the two bridges is 2 feet 6 inches; and although it now commences to fall at both places, it sinks most rapidly at the Britannia; so that three-quarters of an hour after high-water at the Menai, when the difference is at a maximum, there is a fall of 3 feet in a mile between the two bridges, and in spring-tides considerably more. At this time an immense flood of water rushes uninterruptedly through the Swellies, the rocks being wholly or partially covered. As the tide falls, however, the difference of level and consequent velocity diminishes, and at length, five hours and three-quarters after the tide turned at Britannia, it is again reversed, and commences to flow in from Carnarvon. This change of direction, however, does not arise from the new tide-wave entering at Carnarvon, as might be supposed, but commences at the Swellies while the tide is yet ebbing out at Carnarvon, and forty minutes before the water becomes slack there. This is occasioned by the comparatively open channel at Beaumaris, which draws off the water so rapidly that it overtakes the Carnarvon ebb before it is complete, the water dividing between there and the Swellies and ebbing for a short time in two opposite directions.

We have now arrived again at the point from which we started, viz. where the new tide is just entering at Carnarvon. We have seen, however, that its flow is later than that at the Swellies by forty minutes. While, however, the tide rises and gains strength at Carnarvon, it continues still to fall and flow out at Beaumaris. This continues for two hours before the difference of level between the two bridges attains its maximum, which is about 3 feet 6 inches. At this time the water pours in over the rocky channels of the Swellies with extraordinary violence, and, at one point, creates a foam and noise, which may be heard at a great distance, and have given the locality its name and celebrity. The time of low-water does not coincide with that of slack-water at either place; for at the Britannia it continues to fall an hour and a quarter, and at the Menai Bridge two hours, after tide-turn, in consequence of the yet falling tide of Beaumaris.

We have purposely omitted allusion to the Beaumaris tide, to prevent confusion; its course, however, is such as might be expected from a consideration of the locality. At the time the tide-wave first passes Carnarvon, its influence has not reached Beaumaris, and the preceding tide is still ebbing out. The fresh supply entering at Carnarvon flows entirely through the Straits, and only tends to increase the ebb. It, however, arrives in such quantity as to have a sensible influence on the height of the tide; and the time of *low*-water is attained an hour and a half before the tidal wave has found its way round the island and occasioned *slack*-water. After this, however, it continues to enter both at Beaumaris and Carnarvon, the two tides meeting at a point between Menai Bridge and Beaumaris; and the time of high-water is attained about fifteen minutes after that at the Menai, and more than an hour after the Britannia. The falling tide at Carnarvon now draws off such a quantity of water through the Straits, that although sinking, it continues to flow in at Beaumaris until nearly two hours after tide-turn, and three hours and a quarter after tide-turn at the Swellies; after which time the direction at Beaumaris is changed, and it flows out at both extremities of the Straits.

This complicated series of changes will be better understood by regarding the long channel between Carnarvon and the Swellies as a great basin, into which the nascent tide enters, while at the other end it is yet emptying itself towards Beaumaris. After a time, the tide begins to enter from Beaumaris, the basin becomes filled, and the tide, falling at Carnarvon, but continuing to rise at Beaumaris, pours uninterruptedly through the Straits with great velocity. It, however, ebbs so freely at Carnarvon, that the water in the basin sinks, although at the Menai Bridge and Beaumaris it continues to rise until the summit of the tide-wave has passed by; after this the water retires at both ends of the Straits until low-water. The quantity of water which flows through the Swellies in the direction of Carnarvon is probably twice as great as that which passes in the direction of Beaumaris.

The levels of the tide furnish another point of interest. At Carnarvon, the high-water occurs about twenty minutes after slack-water, and during the interval the water rises about 2 inches. At the Britannia, the high-water is also twenty minutes after slack, the water rising 6 inches in the interval; but at the Menai, high-water is not attained till eighty minutes after slack, and the difference of level is 21 inches. Similarly, the low-water at Carnarvon does not occur until twenty-five minutes after slack, the tide falling 8 inches. At the Britannia, the low-water is an hour and a quarter after slack, and the difference of level 2 feet; and at Menai Bridge nearly two hours, the tide falling 4 feet in the interim.

At Beaumaris, on the contrary, high-water is attained two hours *before* tide-turn, the water sinking 6 feet, although still pouring into the Straits; and the low-water occurs ninety minutes *before* tide-turn, the water rising in the interval, although flowing out of the Straits.

The difference of level between high and low-water at

	Feet	Inches.
Carnarvon is	11	3
Britannia	13	2
Menai Bridge	17	4
Beaumaris	17	8

We are now speaking of a comparatively low tide. In spring-tides, assisted by winds, a difference of 23 feet has been observed at the Britannia Bridge, and as much as 30 feet is said to be sometimes observed at Beaumaris.

The contemporaneous tide-waves of the different parts of the Straits divide themselves naturally into two pairs; the Carnarvon and Britannia tides are the earliest, occurring about the same time, and rising to the same height.

The Britannia wave, however, sinks somewhat lower, from the quantity which flows through the Swellies towards Beaumaris.

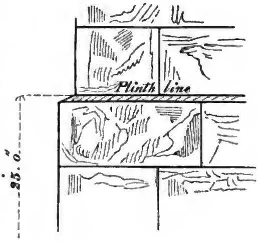
The Menai Bridge and Beaumaris form the other pair, rising and falling through a much greater space than the others, and occurring considerably later.

The following table shews the relative periods of an ordinary tide at the four different places:—

Carnarvon.		Britannia Bridge.		Menai Bridge.		Beaumaris.	
	h. m.		h. m.		h. m.		h. m.
Tide-turn (towards S.W.)	0 16	Tide-turn (towards S.W.)	0 6	Tide-turn (towards S.W.)	0 0	Tide-turn (towards N.E.)	3 24
High-water ..	0 36	High-water ..	0 26	High-water ..	1 20	High-water ..	1 34
Tide-turn (towards N.E.)	6 30	Tide-turn (towards N.E.)	5 50	Tide-turn (towards N.E.)	6 4	Tide-turn (towards S.W.)	9 36
Low-water ..	6 54	Low-water ..	7 6	Low-water	7 56	Low-water ..	8 6

At Plate XXIX. will be found a diagram, representing the observed heights of the tide at high and low water at Britannia Bridge, during the month of September 1849, and shewing their dependence on the moon's age, or, rather, on the time of her transit. The upper division of the Plate contains four zig-zag lines, two of which are plain lines, and two dotted; the upper line represents the height of the tide at high-water for each consecutive tide in the month. Its zig-zag appearance is owing to what is called the *diurnal inequality* of the tide; it is a phenomenon dependent on the moon's north or south declination, and it causes the night tides to be higher than the alternate morning tides, or the reverse. When the moon has no declination, there is no inequality.

The lower line similarly represents the height of the tide at low-water; the diagram shews that while the range of spring-tide is 20 feet, the rise of a neap-tide may be less than 7 feet; the two intermediate dotted lines shew the height at the times of slack-water; and it may be seen from them that the tide rises pretty constantly 8 inches after tide-turn at high-water, and falls 1 or 2 feet after tide-turn at low-water; the mean level of the sea is indicated by a dotted line at the level of 10 feet 3 inches. The datum from which all these heights are measured is a point 25 feet below the plinth of the Britannia Bridge; it is the datum from which all the floating operations were calculated, and coincides very nearly with the lowest water of spring-tides. The plinth of the Menai Bridge is 3 inches higher than that of the Britannia, or corresponds to the level of 25 feet 3 inches.



The lower half of the Plate contains four lines which are called the *curves of semi-menstrual inequality.* In this diagram the graduations refer to the *time* of the tides, and not the height, as in the preceding one—the divisions in the vertical scale representing hours; the principle on which it has been constructed is as follows:—The dependence of the tides upon the motions of the moon is well known, and although the moon makes only one apparent daily revolution, yet there are generally two tides in this day. The cause of this apparent anomaly is explained in Herschel's "Astronomy." One of these tides usually follows pretty closely after the transit of the moon, and the other one succeeds it at an interval of about twelve hours, so that there are always two high-waters rolling round the earth, one of which is on the opposite side of the globe to the other.

Theoretically, high-water should occur at the time when the moon is passing over the meridian of any given place—but practically, the tide-wave is obstructed in its course over the ocean, and the summit of the wave, or high-water, does not reach a place until some time after the moon has passed its meridian—commonly two or three hours. This interval of time, between the moon's passage and high-water, is called the *lunitidal interval.* And were the moon alone concerned in the phenomenon, this interval would be a constant quantity, and tide-tables would be unnecessary, for by adding a constant to the time of *moon's southing*, as given in the almanacs, we should obtain the time of high-water at all seasons.

But the sun raises a daily tide as well as the moon, and although smaller in its amount its effects are very sensible, occasioning the difference between spring-tides and neap-tides. The sun causes a wave to roll round the earth similar to but smaller than the lunar wave, and independent of it; when the two waves coincide they produce high or *spring*-tides, and when they do not coincide they oppose, and tend to neutralise each other, and we experience low or *neap*-tides. The former case occurs when the sun and moon both transit about the same time, that is to say, at twelve o'clock—we have then new or full moon, and consequent spring-tides; the neap-tides occur when the moon is in her first or third quarter, and souths about six o'clock; the solar wave then passes six hours before or after the lunar wave, the low-water of one coinciding with high-water of the other, thus tending to neutralise each other. The lunitidal interval and consequent time of high-water is also affected in a similar manner, being accelerated or retarded according as the solar wave precedes or follows the lunar wave.

In the diagram, the lunitidal intervals for each tide in the month are plotted on a vertical scale, and the upper line is a line drawn through all these points, the difference of time varying from eight and a half hours to ten and a quarter hours; this difference is called the *semi-menstrual inequality.* The average lunitidal interval is nine hours fourteen minutes, that is to say, the high-water at Britannia Bridge occurs on an average nine and a quarter hours after the moon has passed over that meridian. The remaining three lines are similarly curves, formed by the lunitidal intervals of low-water and tide-turn; their slightly zig-zag form being due to diurnal inequality.

These diagrams may be used as a perpetual tide-table for the Britannia Bridge; it is only necessary to enter the table with the time of the moon's southing, as given in an almanac, and the time and height of the corresponding tides are seen by inspection; for example, whenever the moon transits or souths at one o'clock, we expect spring-tides, the time of high-water being nine hours after the moon's transit, or at seven o'clock; and similarly, by adding the lunitidal intervals of low or slack-water, we may obtain their periods. The principal circumstances disregarded in this method are the diurnal inequality and the state of the wind and the barometer; an addition of sixteen minutes should also be made to the time of the moon's southing to compensate for the difference of longitude between Greenwich and Britannia Bridge.

The time of tide-turn, or what is practically considered high-water in the Swellies, may be conveniently obtained in Greenwich time by subtracting two hours from the time of high-water at Liverpool, as given in the Admiralty tide-tables. This will give the time with sufficient accuracy for practical purposes; the time of slack or low-water will be about six and three-quarter hours afterwards, the tide flowing on an average six hours eight minutes, and ebbing six hours and forty minutes.

It is customary among sailors to deduce the time of high-water on any given day from the *establishment* of the port, that is, the turn of high-water at any place on the day of new or full moon; and where the tides are regular, by adding forty-eight minutes for every day of the moon's age to this quantity, they obtain, approximately enough, the time of high-water; for the moon's transits occur upon the average forty-eight minutes later every day. Now the establishment of any port is that lunitidal interval which corresponds to the hour of twelve; for when the moon souths at twelve it is necessarily new or full moon. At the Britannia Bridge the establishment is about *nine hours twenty minutes*, or nine hours, if we regard the time of tide-turn. By multiplying the moon's age, then, by forty-eight minutes, and adding the product to nine o'clock, the time of high-water at the Swellies may at all times be obtained for nautical purposes.

APPENDIX.

THE CONTRACTS AND COST OF THE BRIDGES.

It will be interesting to the professional reader to possess some account of the cost of these structures, and of the parties employed in their construction. Although in large works of a novel character it is usually bad policy to proceed by contract, yet this rule was departed from under the peculiar circumstances of this case; and it was Mr. Stephenson's wish from the commencement that the arrangement with the contractors should be principally confided to Mr. Fairbairn, on account of his practical knowledge of such matters. That gentleman had been employed by Mr. Stephenson, on his own responsibility, since the month of April 1845 in carrying on the preliminary experiments as described. But in order that he might be empowered to sign certificates, &c., it was necessary that his appointment should be sanctioned by the Board; this was accordingly done, on Mr. Stephenson's recommendation, by a Board Minute, dated May 13, 1846, and he continued to superintend the financial arrangements until May 1847, when, on account of some misunderstanding between him and the Board, this department was intrusted to the Author.

Mr. Fairbairn had proposed, July 1845, to undertake the whole construction himself; this proposition was not, however, entertained, and in the month of July 1846 circulars were sent to some of the principal iron-masters, Messrs. Thornycroft, Messrs. Bradley, Messrs. Bramah, Barrows and Hall, and Walter Williams in Staffordshire, the Coalbrook Dale Company in Shropshire, and the Butterley Company in Derbyshire; and the manufacture of the plates was contracted for by these houses at per ton according to the weight of the plates: the average price of all the plates was 15*l.* per ton, the price of iron being then, unfortunately, remarkably high, and the iron-masters generally overwhelmed with orders. It was thought better that the Company should purchase their own iron, and themselves supply the contractors for the construction of the tubes, in order to insure the best quality, and that it might more immediately be subject to Mr. Stephenson's examination. The iron was consequently supplied to the contractors throughout the construction of the bridge at 15*l.* per ton, however the market price might vary. It was important that the plates should be truly sheared by the manufacturer, to avoid subsequent expense, and great difficulty was then found in getting the 12-feet plates for the bottom, either sufficiently accurate in dimensions or correctly sheared. The unusual size of the T-iron gave, moreover, some trouble, and considerable delay occurred in consequence. Special shears and rolls were, however, put up by most of the iron-masters to meet these requirements, although it was ultimately found requisite to pass the plates cold through rollers at the works to take out the buckle, and to shear them all still farther to ensure accuracy in the plating. A little difficulty also occurred with respect to a very peculiar dictionary of technical terms in use among these gentlemen, which it is very useful to understand.

It was essential to use the finest possible quality of iron for so important a work, and the contracts accordingly were entered into, specifying "the best plates." On finding, in some instances, these plates very inferior, and on making inquiries on the subject, it was discovered that among the iron-masters the word "best" means, literally, the ordinary quality of plates, or common iron; the term "best-best" being applied to plates of a higher price, and even "best-best-best" being sometimes applied to signify what, in our ignorance, we imagined to be expressed by "best." A higher price for good iron was accordingly demanded and paid.

The drawings for the bridge being sufficiently advanced in August, Mr. Stephenson instructed Mr. Fairbairn to proceed with the letting of the contracts for the construction; and as he was obliged to leave England for a few weeks, he wished this to be done during his absence to avoid any delay. He had conferred with the Board on the subject, and had estimated the cost of construction at from 27*l.* to 30*l.* per ton, the Company finding the iron at 15*l.*; so that the price for the workmanship would be from 12*l.* to 15*l.* per ton. It must be remembered that there was then a double row of cells at the bottom of the tube; and Mr. Fairbairn proposed to construct the tube in sections at the works of each contractor, to rivet these sections together as far as practicable, and ultimately to ship these pieces to the spot, and there put them together at the expense of the Company. This proposal involved the carriage of the plates from the iron-masters to the various works, and back again into North Wales, and doubtless arose from an undue consideration of the nature of the work, and from the fact that it is not unusual to construct iron vessels of considerable size in this manner for foreign exportation. The specifications were submitted by Mr. Fairbairn to a limited number of manufacturers whose premises were sufficiently extensive. In a work, then so entirely novel, the difficulty of handling heavy plates, and of actually riveting through so many thicknesses, was most erroneously overrated. It is certain that Mr. Stephenson's estimate was too high, whereas the prices specified in the tenders that were submitted to the Board in September were 34*l.* and 35*l.* 7*s.* 6*d.* per ton. These tenders were, however, at once rejected, and it was determined to submit the specifications to more open competition; and, at the request of the directors, other parties were invited to tender. An extract from Mr. Fairbairn's letter to Mr. Stephenson of the 26th of September, 1846, will give the names of the various firms applied to:

> "Had the tenders given in by the different parties been satisfactory, it was my intention to have recommended the following distribution of the work:—

			Feet.
Fairbairn and Sons, Conway		450	= 1200
Ditto,	one-fourth of Britannia Bridge	750	
Ditchburn and Mare, Conway		450	= 920
Ditto,	one span of Britannia	470	
Miller and Ravenhill, one-fourth of Britannia			750
Blyth and Co., one span of Britannia			500
Vernon and Co., two of the short spans			530
	Total length		3900

> "From this you will perceive that I have apportioned to Millwall the lion's share, but I did so not so much from a desire to have more than others, as to expedite the work and to have the whole executed in a satisfactory manner. It is, however, now doubtful whether any of the parties selected will have the making of the tubes, should the offers from others be much under their tenders. You will, however, learn further on these points when you have occasion to see the parties in Moorgate Street.
>
> "At the request of the Directors circulars have been sent out to R. Napier, Glasgow; Tod and Macgregor, Glasgow; Scott and Sinclair, Greenock; Caird and Co., Greenock; the Great Western Co., Bristol; James Lillie and Son, Manchester; Rothwell and Co., Bolton; Hick and Co., Bolton; Horton, Brierly Hill, Wolverhampton. These parties will either call upon you in Great George Street to consult the drawings and specifications, or upon me here, where copies are retained."

During these negotiations other parties also were invited to tender, and Mr. William Evans, then employed in the erection of the masonry for the Conway Bridge, and in other works on the line, and Messrs. Garforth, of Dukinfield, near Manchester, having inspected the drawings and specifications in Mr. Stephenson's office, proposed also to tender for the tube. At the Board meeting on October 14th, the construction of the Conway Bridge was accordingly let to Mr. Evans, who undertook to deliver the work in sections at Conway, at 28*l.* per ton, but strongly advised the construction of the tubes entire on the spot, and agreed to erect the necessary workshops, scaffolding, and machinery for that purpose, to provide also the presses and pontoons, and under the immediate inspection of Mr. Stephenson, or according to his directions, to place the tubes in their place at 37*l.* per ton.

One thousand tons of the Britannia Bridge were at the same time let to

Messrs. Garforth, to be put together at their works at 30*l.* per ton; and 1500 tons to Mr. Horton of Brierly Hill, at the same price.

On the 23d of October the remainder of the Britannia Bridge was let to Mr. Fairbairn and Mr. Charles Mare of Blackwall, at 32*l.* per ton.

Summary.

	Tons.		£.	
Mr. Fairbairn	2000	at	32	To deliver at the Straits in sections.
Messrs. Ditchburn and Mare	2000	at	32	Ditto.
Messrs. Garforth	1000	at	30	To deliver at Liverpool.
Mr. Horton	1500	at	28	Ditto.
Mr. Evans	2000	at	37	For the whole Conway Bridge, including floating and lifting.
	8500			

The terms of these tenders will be better understood from the following correspondence:—

"*To the Directors of the Chester and Holyhead Railway.*

"Millwall Works,
"September 8th, 1846.

"Gentlemen,

"We are willing to contract for the construction of the riveted metal plates required for the proposed tubular bridges at the Conway, and at the Menai Straits, at the rate of 35*l.* 7*s.* 6*d.* per ton,—thirty-five pounds seven shillings and sixpence per ton.

"The whole of the plates, angle-iron and T-iron, being supplied to us at the rate of 15*l.* per ton.

"At the above rate we will deliver the work alongside a vessel in the Thames, in pieces of such form and size as may be found convenient for the purposes of shipment.

"We are, Gentlemen,
"Your most obedient servants,
"Wm. Fairbairn & Sons."

"Chester and Holyhead Railway,
"61 Moorgate Street, 15th October, 1846.

"Sirs,

"Referring to the tenders (laid yesterday before the Board of Directors) for the construction of the tubes for the proposed bridges across the Conway and the Menai Straits, I beg to inform you, that the terms of your offer, as regards price, are not such as to meet their acceptance.

"I am, Sirs,
"Yours obediently,
"George King, *Secretary*.

"Messrs. Wm. Fairbairn and Sons,
"Millwall."

"Millwall, Poplar,
"October 19th, 1846.

"Sir,

"Since the receipt of your letter of the 15th instant, informing us that our former offer for the construction of the tubular bridges required for the Chester and Holyhead Railway Company, was not such, as regards price, as to meet with the acceptance of the Directors, we have very carefully reconsidered our calculations, and having placed ourselves in communication with Messrs. Ditchburn and Mare, and consulted with them, who feel disposed to enter largely into the business now, we beg to make the following proposal for the consideration of the Board:

"Provided the Directors will divide the remainder of the order for the Britannia Bridge (and which, we understand, will amount to about 4000 tons of riveted plates) in equal portions between the two firms, we should be willing to complete our portion of the contract in accordance with the drawings and the terms of the specification, and deliver the same painted, and marked ready for re-erection, for the sum of thirty-one pounds five shillings per ton (31*l.* 5*s.*), or delivered at the Straits (32*l.* per ton) thirty-two pounds per ton, receiving from the Company the iron at the rate of fifteen pounds per ton.

"We would point out to you, that it is the increased quantity which we now ask which alone enables us to make this offer; because not only does the charge per ton for outlay in machinery, tools, scaffolding, &c., diminish as the quantity to be executed is increased, but we believe the amount of wages would be regulated in like manner.

"We should much wish to have the matter brought before the Directors at an early period, as the prospect of a contract of this magnitude interferes with our acceptance of other work.

"We are, Sir,
"Your obedient Servants,
"W. Fairbairn & Sons.

"George King, Esq.
"Chester and Holyhead Railway."

"Chester and Holyhead Railway,
61 Moorgate Street, October 21, 1846.

"Sirs,

"I am instructed to accept the offer made in your letter of the 19th instant, to construct one-half of such portion of the tubes for the Britannia Bridge, Menai Straits, as were then uncontracted for, at the sum of 32*l.* (thirty-two pounds) per ton, receiving from the Company the iron at the rate of fifteen pounds per ton; such price to include the completion of the same in accordance with the drawings and the terms of the specification (as to time, and all other particulars), and the delivery by you, at the Menai Straits, of the said portion of the tube, painted and marked ready for erection.

"The quantity previously contracted for, for the Britannia Bridge, is 2500 tons; of the remainder, whatever it may be, one-half is agreed by the Directors to be contracted for with you, agreeably to the conditions above referred to.

"Be pleased to acknowledge this letter, confirming the acceptance by yourself, and expressing your readiness to enter into a contract (whenever required to do so), with sureties, to be approved of by the Company, for the due performance of the said contract.

"The drawings and specification be pleased to sign at once.

"I am, Sirs,
"Yours obediently,
"George King, *Secretary*.

"Messrs. Fairbairn and Sons,
"Millwall, Poplar."

Similar arrangements were made with the other contractors, and the contracts were subsequently formally drawn up and entered into.

The arrangements being so far complete, the iron-masters commenced rolling the plates, and at the close of the year 1846 some cargoes were ready for delivery.

Mr. Evans had also nearly completed his workshop and machinery at Conway, and had commenced the construction of his platform, on which the first tube was to be built.

The sections in which the contractors had undertaken to deliver the tubes were so large that it became almost impossible to comply with the terms of the contracts, and it was consequently proposed to construct the tubes on the spot.

The satisfactory manner in which Mr. Evans was conducting his work at Conway was a further inducement for adopting the same plan at the Straits.

Mr. Stephenson became very anxious for such an alteration to be made, and the Author was instructed to put himself in communication with the various contractors, and at once take the necessary steps towards remodelling their agreements. After numberless debates and propositions the arrangement now finally come to will be understood from the following extracts from minutes of the Board, dated 12th May, 1847. It was reported to the Board that Messrs. Ditchburn and Mare had made some progress,—that Messrs. Fairbairn and Son had sold their contract to Mr. Mare. That the Directors regretted extremely they had not been previously communicated with, and consulted upon this subject, and that they would have preferred to have had the option of making other arrangements themselves, and did not feel disposed to make a contract with any one firm for the construction of so large a portion of the tube. The Board, therefore, temporarily retained Mr. Fairbairn's liability, and it was agreed that the Company should provide platforms and workshops; on which conditions Mr. Fairbairn and Mr. Mare agreed to complete the work at the Straits at 35*l.* per ton, finding themselves the necessary machinery. An agreement was made with Messrs. Garforth on similar terms at 34*l.* 10*s.*; and in consequence of the inadequate means which Mr. Horton appeared to possess for carrying on his portion of the contract, he was for the present desired to stay further proceedings. And as Mr. Fairbairn, on his original appointment, had been empowered to sign certificates, he being now an interested party, it was ordered that all future certificates should be signed by the Author on the part of Mr. Stephenson.

The contracts for the supply of the chains and the hydraulic presses were at the same time entered into, and the tender of the Bank Quay Company for the supply of the cast-iron work was accepted, the price for castings being then 7*l.* 10*s.* per ton. Immediately after this period Mr. Fairbairn's arrangement with Mr. Mare for the sale of his portion of the contract was sanctioned by the Board. A similar arrangement also took place between Mr. Horton and Mr. Mare. In conformity with these arrangements the bridges have been since constructed as follows:—

The whole of the Britannia Bridge, excepting one large tube—Mr. Charles Mare, of Blackwall.

One large tube for the Britannia Bridge—Messrs. Garforth, of Dukinfield, near Manchester.

The whole of the Conway Bridge, including masonry—Mr. W. Evans.

The masonry and platforms of the Britannia Bridge—Messrs. Nowell, Hemingway, and Pearson.

The cast-iron work of both bridges—The Bank Quay Foundry, Warrington.

The hydraulic presses, &c. for raising—Messrs. Easton and Amos, the Grove Iron Works, Southwark.

The chains—Messrs. Howard and Ravenhill, London.

Soon after this period the whole of the experiments, both by Mr. Hodgkinson and Mr. Fairbairn, were completed. As the great cost of such investigations is not generally known, the following analysis may prove interesting:—

	£	s.	d.
MILLWALL EXPERIMENTS.			
Small tubes for preliminary experiments	483	14	0
The large model	320	0	0
Repairs, two first experiments	197	15	0
Ditto, two last ditto	402	18	4
Draughtsmen at Millwall	100	0	0
MANCHESTER EXPERIMENTS.			
Various expenses in constructing models, Jan. to June 1846	761	17	11
Ditto ditto, July to Dec. 1846	1037	5	10¼
Rent of ground, three-quarters of a year	112	0	0
Materials purchased	119	4	5
Professional charges, personal expenses, draftsmen, &c.	1757	10	8
	5292	6	2¼

Subsequent charges by Mr. Fairbairn raised the amount to 6530*l.* Some discussion on the subject of these charges, coupled with their disapprobation of the transfer of his contract, and of other arrangements, caused some misunderstanding between the Directors and Mr. Fairbairn, which led to his tendering his resignation soon after May 1847. At the instigation, however, of Mr. Stephenson, this resignation was withdrawn, and though not in any active capacity, he continued to assist Mr. Stephenson, in conjunction with the Author, in watching the progress of the manufacture of the Conway Bridge; and though he took no share in the arrangements for floating or raising, he occasionally visited the works, and was present at those operations in March 1848; but his resignation being again tendered in the month of May, it was then accepted, and since that period he has been in no way connected with the works. A patent was, however, obtained by that gentleman in October 1846, under the following circumstances. Immediately on the completion of the preliminary experiments, Mr. Fairbairn foresaw that wrought-iron girders on a small scale would eventually come into use for general purposes, and, on account of their not being liable to fracture from heat, in fire-proof buildings, which is frequently the case with cast-iron beams, he proposed to Mr. Stephenson to take out a patent for wrought-iron girders on a small scale, which he hoped might prove advantageous to him. To this Mr. Stephenson consented, but was averse to his own name appearing in the patent, and refused to partake in any share of the profit, though he consented to pay half the expenses of obtaining the patent. The following letters will explain the subject:—

"Manchester, October 10, 1846.

"My dear Sir,

"You will remember a conversation which we had about taking out a patent for hollow sheet-iron girders for bridges and other purposes. One-half of that patent was to be yours and the other half mine; and I am now informed by Messrs. Newton and Son, of Chancery Lane, that the patent is sealed, and therefore only wants our confirmation.

"I have remitted them one-half of the money, and if you will oblige me to send the gentlemen a cheque for the remaining half, 60*l*., the patent will be secured and all correct.

"Mr. Hodgkinson will join me on Monday by the express to London, and hoping to find you disengaged on the following morning, as before arranged, &c.

"To Robert Stephenson, Esq."

"Manchester, October 27, 1846.

"My dear Sir,

"I am much obliged by your letter of yesterday, and particularly for that part of it which relates to the original idea of the bridge; I was sure it was yours in every respect: but there is nothing new, or likely to turn out valuable, but there immediately start up a hundred claimants. We are all subject to this species of mental encroachment; but in your case everything is now clear, and no person can possibly establish a prior claim.

"At all times you may rest assured of my best efforts in supporting the claim to which you are so justly entitled.

"Yours faithfully,
"William Fairbairn."

This patent was obtained, and in December 1846 the following letter was written by Mr. Fairbairn:—

Manchester, December 31, 1846.

"My dear Sir,

"Now that we have got the patent for the hollow girder bridge, will you inform me what we should charge as a patent right to parties who choose to use it? I have been thinking of 20*s.* per foot of span; or, in case you consider that sum too much, it might be reduced to 15*s.* per foot.

"I wish you could find time to give me your opinion on these points, as I have several applications about them, and should like to have some definite charge of a moderate kind.

"To Robert Stephenson, Esq."

Mr. Stephenson appears to have thought no more about the subject until the 6th of June, 1847, when, in alluding to the girder which failed in the Dee Bridge, Mr. Fairbairn observes:—

"Allow me to direct your attention to the hollow sheet-iron beams I am now making for a similar bridge of 100 feet span. In these you will find strength, lightness, and security, to any extent; and, although there may be some objections to them, on account of their being new and untried, you will at once pronounce them superior to anything yet made," &c.

In answer to this letter Mr. Stephenson replies, June 8th, 1847:—

"I observe what you say respecting the tubular girders you have made; when we meet we must discuss the matter, for, having already erected these bridges, and having designed them for a much longer time, I see that your claim for these tubes, as applied to bridges instead of to fireproof buildings, which was what I understood when you proposed to take out the patent, is likely to create considerable inconvenience in carrying out some contracts which have been let.

"I have had this matter brought prominently before me within the last few days, which induces me to refer to it now, as it forms a topic in your note received this morning."

Again, on the 9th of June, Mr. Fairbairn observes:—

"You must have forgotten that I mentioned all the particulars about the patent when you requested it might be in my name, and I once or twice consulted you as to what we should charge for a license or patent right.

"Your answer was, that nothing was so objectionable as paying for patents, and you instanced your own for the locomotive engine in France.

"The bridges were always included as well as beams for fire-proof buildings, and I have no doubt all the particulars, as well as your own half share of the patent, must have escaped your memory."

Mr. Stephenson does not appear to have alluded to this letter in subsequent correspondence, and Mr. Fairbairn again writes, August 16, 1847:—

"I am drawing up an advertisement for giving publicity to our new patent girder. You are aware it has been taken out in my name; and although I have probably contributed much more than most others in determining its proportions, as regards strength, &c., I, nevertheless, am of opinion that your name should stand at the head of the invention; I do this from a conviction that you are entitled to precedence, not from having worked harder or done more for it than myself, but from the undeniable fact that I should never have thought of the experiments which led to the discovery but for the instructions which I received from you relative to the large tubes.

"These experiments have, unquestionably, led to the developement of an entirely new era in the history of girders and bridges, particularly those of large span. On all these points you must endeavour to steal an hour from your other engagements, and let me know what are your wishes, and I will try to carry them into execution."

The following was Mr. Stephenson's reply to this communication, August 23, 1847:—

"When at Tapton we will discuss your proposed advertisement as to the patent: your view of the matter seems to me just and honourable."

No further written correspondence appears to have taken place on this subject. These girders, however, have come into general use, and the patent right has not been sustained.

The cost of the Conway Bridge was as follows:—

	£	s.	d.	£	s.	d.
Cast-iron	6,887	19	3			
Wrought-iron	28,239	16	3			
Hydraulic presses, proportional part of the whole cost	983	0	0			
Chains	203	0	6			
Experiments, proportional part of the whole	1,306	0	0			
Construction, floating, and raising	69,071	0	0			
				106,690	18	0
Masonry				38,500	0	0
Total				145,190	18	0

The cost of the Britannia Bridge, when nearly complete, was estimated as approximately as it could be ascertained as follows:—

	£	
Pedestals, wing walls, Carnarvon	17,459	
Carnarvon Tower	28,626	
Britannia Tower	38,671	
Anglesey Tower	31,430	
Pedestals, wing walls, Anglesey	40,470	
Lions	2,048	
		158,704
Wrought-iron used in tubes	118,946	
Cast-iron in tubes and towers	30,619	
Construction of tubes	226,234	
Pontoons, ropes, capstans, painting materials, &c.	28,096	
Raising machinery	9,782	
Carpentry and labour in floating, raising, and completing the bridge	25,498	
Experiments, proportional part of the whole	3,986	
		443,161
Total		£601,865

Persons practically employed in the Erection of the Britannia and Conway Bridges.

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John Francis, Draughtsman.
Thomas Ellis Rawlinson, Clerk of Works.
Isaac Wood,
Alexander Johnson, Inspectors.
Allan Vickers,

Construction and Erection of Tubes.

Latimer Clark, Assistant Engineer.
John McLaren, Superintendent of Ironwork.
Charles Rolfe, Inspector of Ironwork.

William Dempsey,	Draughtsmen.
Henry Heyerdahl,	

John Watts, Foreman of Mechanics.
Henry Muirhead, General Foreman of Works.

George Whitting,	Foremen of Sailors.
Luke Roberts,	

William Pope, Foreman of Carpenters.

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John Lister, Contractor's Engineer.
John Lister, Jun., Draughtsman.

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George Whitting,	
Luke Roberts,	
Charles Holt,	
Isaac Holt,	

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